

The Oil Palm

Fourth edition

R.H.V. Corley and P.B. Tinker

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Preface to the fourth edition

This is the fourth edition of Hartley's *The Oil Palm*, and the first one not prepared by the late C. W. S. Hartley himself. It may be useful for readers who do not have access to the third edition to read the Prefaces that Hartley wrote, so they are reprinted here. They, and the books themselves, give an excellent view of how the oil palm industry has grown and thrived in the last half century. It is no easy task to write a new edition of a book that has already become a classic, and we have done our best to measure up to it.

The first purpose of this new edition is of course to bring the book factually up to date. The total value of the annual output of the industry at present prices is some US\$7 billion, so it is by any standard now a major crop. Change has been rapid and pervasive, both in the commercial and scientific spheres. This alters the purpose of this book to some extent. The earlier editions aimed to be all-encompassing, and they contained a mine of detailed information gathered by Hartley in half a century of work with the oil palm in all parts of the world. This is no longer so appropriate, if indeed it were still possible. We have therefore aimed to condense parts that deal with site-specific and local information, and to pay more attention to emphasising the underlying principles. We have also tried to start many sections with a brief synopsis of the general scientific background to particular issues, with the intention of presenting the oil palm industry in relation to agricultural science in general.

In some ways the oil palm research community is still rather insular. It is surprising how much of the oil palm scientific literature only appears in more or less local scientific conferences, or in the 'grey literature'. This may not be abstracted by the major literature abstracting services, or not appear on the on-line scientific information services. The last are now becoming the standard way in which scientists access the literature, and we believe strongly that the oil palm industry must take account of this. Much of the oil palm literature is well up to international standards, and should appear in international journals, to get proper exposure.

A further difficulty with the oil palm literature is that there are quite often inconsistencies in the way Malay and Chinese authors' names are written, with the same author sometimes giving his or her name in different ways on different papers. This does happen with Western authors also, but much more rarely. Where possible, we have tried to standardise the format for each author, but a result is that we have sometimes quoted a name in a different form to that on the actual paper.

We have consciously tried to stand back from the industry a little, and to relate it more to what is happening in other crops, particularly the other oil crops. With globalisation becoming a reality, competition is steadily increasing, and it is necessary to know and understand the competing industries. This interaction has already occurred strongly in human nutrition, but much less so in the other subjects. A further external pressure is that the industry is often targeted by environmental activists (see Chapter 15). Much of their criticism might more easily be shown to be baseless if the research literature on the crop was easily and generally accessible, so that the industry was more transparent to outsiders. This is particularly true for research aimed at environmental issues.

The shift in coverage in the book means that a number of references that appeared in earlier editions have now been omitted. Where more extensive information is available in these, we give a reference to the third edition, as Hartley (1988). A particular problem was presented by the numerous observations based on Hartley's own extensive international experience, and unsupported by references. Where necessary, we have cited Hartley (1988) in support of such observations, and his reputation is a guarantee of their accuracy.

Both of us were friends and colleagues of Charles Hartley, and we are proud to carry forward his book into another edition. He first worked as an Agricultural Officer in Malaysia, and was taken prisoner in the second world war. He was a man of great strength of character and physical toughness, as shown by his three years of forced labour on the Thailand–Burma Railway, after which he went on to make a distinguished career in the oil palm industry. Even in his eighties he survived a serious car accident in Ecuador, but quite soon afterwards returned to continue his business in that country, where he owned a small plantation.

He made his mark as Deputy Director and later Director of the West African Oil Palm Research Institute, which under him became a major centre for new advances in oil palms. After retirement he travelled the world as a consultant, and was in great demand in all oil palm-growing countries. He was probably the most respected oil palm expert in the world during this time, and made many friends within the industry. His work was always thorough, responsible and of a very high standard, and he amassed an enormous fund of detailed information on the culture of oil palms in all the major growing areas. This wide and deep knowledge was an important characteristic of *The Oil Palm*, and gave it great authority.

We are glad to have known Charles and worked with him, and have no doubt that he will be remembered in the oil palm industry for a very long time.

Hereward Corley
Bernard Tinker

Preface to the third edition

The great expansion of oil palm planting in many parts of the world, but especially in South-east Asia, has continued during the last decade, and the availability of oil palm products on the world market has tripled during the period while at the same time consumption has increased dramatically in the producing countries themselves. In revising this book for a third edition opportunity has been taken to reduce its length by shortening the parts which deal with subjects, such as the palm groves, which are now of less agricultural or commercial importance, and to introduce the important new work on prospection, selection and breeding, tissue culture, pollination, pests and diseases, nutrition and mill sludge disposal.

As before, I am indebted to many organizations and individuals for helpful discussion and the provision of data, and I am especially grateful to Mr A. D. Marter of the Tropical Development and Research Institute for helping me update the statistics in Chapter 1, Dr J. A. Cornelius of the same Institute for assistance with Chapter 14, Dr R. H. V. Corley for the provision of photographs and information on tissue culture, and Dr van Heel for electron microscopy photographs of inflorescence development.

Preface to the second edition

For this new edition the text has been extensively revised. It is now ten years since the manuscript of the first edition was completed and since that time there has been great progress in research and an unprecedented enlargement of planted areas in Asia, Africa and America. Chapter 1 has been brought up to date and the widely different development methods being employed are discussed in this chapter and in Chapter 8.

In the revision of Chapters 3 and 4 particular account has been taken of the progress made in relating climate and soil to yield and of the work on growth analysis which has given a better understanding of the palm's performance under varying environmental and cultural circumstances. The part of Chapter 3 which deals with the African palm groves has been severely reduced as these areas are of dwindling importance in the total supply of oil palm products.

In Chapter 5 the recent work on heritability and on interspecific hybridization with the American oil palm is now incorporated. Methods of breeding currently employed are compared, while the latest prospections for new material and the research on growth factors in relation to selection and breeding are described.

Chapters 6 to 10 have been revised to take account of the progress made in cultural practices while Chapter 11 has been extensively rewritten and rearranged to allow for the substantial body of new data on many aspects of the nutrition of the palm. Chapter 13, on diseases and pests, has been brought up to date and expanded. In Chapter 14 the new work on oil quality is discussed and information is given on the oils of the American oil palm and the inter-specific hybrid; reference is also made to new developments in both large and small mills.

Once again I am indebted to many research workers and organizations for assistance. In particular I wish to thank Mr A. H. Green and the Unilever Plantations Group for permission to quote from their Annual Reviews of Research, Messrs Harrisons and Crosfield for permission to make use of material from their Oil Palm Research Station Annual Reports, the Director of NIFOR, Nigeria, for supplying data for updating some experimental

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For this new edition, all data have been converted to the metric system. A conversion table has been provided at the end of Chapter 10 on p. 490. Fifteen new plates and eleven new text figures have been provided.

Preface to the first edition

During recent years there has been a considerable expansion of oil palm acreages in tropical Asia, Africa and America, and interest in the crop has been steadily increasing. At the same time there has been much improvement in the cultivation of the palm following research carried out by research institutes and plantation companies. Of particular value has been the interchange of information between the great producing regions of Africa and Asia and the realization that work done in one continent is often of great import to producers in another. Nevertheless, much of the work carried out has not been adequately published and original papers are sometimes difficult to obtain. It has therefore been my aim to provide in this book a comprehensive account of the oil palm as a plant, of the industry from its early beginnings to its present stage of development, and of the work carried out in all regions to improve cultivation, production and the extraction of the products. In so doing I have tried to interpret the difficulties that have been encountered in various parts of the world, to trace, historically and critically, the reasons underlying certain practices, and to draw attention to the experimental bases, where such exist, for present procedures.

I have been greatly assisted in the compilation of this book by the ready assistance I have received from many quarters. In the first place I have to thank the Managing Committee of the West African Institute for Oil Palm Research (now NIFOR) for assistance given to me and for permission to make use of material being the property of the Institute. Members of the research staff of the Institute, past and present, have contributed much to this book through their work. In particular I would like to acknowledge the help I have had during compilation from Mr G. Blaak, Mr T. Menendez, Mr S. C. Nwanze, Mr A. R. Rees, Mr J. S. Robertson, Mr R. D. Sheldrick, Mr J. M. A. Sly, Dr L. D. Sparnaaij, Dr P. B. H. Tinker and Mr A. C. Zeven; and I am especially grateful to Mr Robertson and Dr Tinker for reading and commenting upon parts of the text and to Mr Rees for answering many queries on problems of germination and physiology generally.

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My task has also been assisted by helpful discussion with research workers of the Institut de Recherches pour les Huiles et Oléagineux, Paris, and I have to thank M. Carrière de Belgarric, Director-General, Dr P. Prevot and M. M. Ollagnier for their friendly cooperation and for putting me in touch with their staff, both in Africa and America.

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C. W. S. Hartley

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Figure 2.5 and Plate 2.4 from Jourdan & Rey, 1997. Architecture and development of the oil palm (*Elaeis guineensis* Jacq.) root system. *Pl. & Soil* 189: 33–48, Figs 3 & 5, with kind permission from Kluwer Academic Publishers and the authors.

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Table 6.1 from Eeuwens, Cargeeg, Lord, Rao & Nelson, 2002. Effects of tissue culture conditions during embryoid multiplication on the incidence of “mantled” flowering in clonally propagated oil palm (*Elaeis guineensis* Jacq.). *Pl. Cell Tissue & Organ Culture* 70: 311–323, Table 5, with kind permission from Kluwer Academic Publishers and the authors.

Plate 12.9 from Corley, 2001. *Oil palm*, in *Tree crop ecosystems* (ed. F.T. Last), 2001, with permission from Elsevier Science.

Figures 4.10, 4.11, 4.18, 8.4, 8.5, 8.14, 10.4, 10.6, 11.1, 11.5, 11.6, 11.7, 11.13, 11.14, 11.22, and Tables 1.10, 3.11, 3.20, 5.4, 5.5, 5.12, 8.7, 8.8, 8.9b, 8.11, 8.12, 10.8, 10.10, 10.11, 10.14, 10.15, 10.16, 10.17, 10.18, 11.5, 11.8, 11.14, 11.17, 11.20, 11.25, 11.29, 11.30 and 11.31 are reproduced by courtesy of The Malaysian Palm Oil Board (formerly Palm Oil Research Institute of Malaysia).

Abbreviations

Abbreviations used throughout the book are listed below. Most are also defined where they are used. Abbreviations used only in a single section are not listed, nor are SI units.

A	Rate of photosynthesis, per unit leaf area
AA AeGIS	Agronomic decision-support system developed by AAR (see Section 11.6.2)
AAR	Applied Agricultural Research (Malaysia)
AFLP	Amplified fragment length polymorphism (see Section 5.2.8.1)
AM	Arbuscular mycorrhiza
$A_{\max}$	Light saturated rate of photosynthesis
APM	Advanced planting material
ASEAN	Association of South East Asian Nations
asl	Above sea level
ASYP	AAR site yield potential model
AV	Anisidine value
AVROS	Algemene Vereniging van Rubberplanters ter Oostkust van Sumatra
AWC	Available water capacity
BP	Before present
BPRO	Breeding programme of restricted origin
BI	Bunch index (ratio of fruit bunch dry weight to total dry matter production)
B.No.	Bunch number (usually per palm per year)
BOD	Biological oxygen demand
BV	Breeding value
B.Wt	Mean weight of a single fruit bunch
Ca	Calcium
CD	Critical soil water deficit
CDC	Critical deficiency content
CGR	Crop growth rate (total dry matter production per unit time and area)
CIRAD-CP	Centre de Coopération Internationale en Recherche Agronomique pour le Développement – Cultures Pérennes
CIRP	Christmas Island rock phosphate
CO ₂	Carbon dioxide
COD	Chemical oxygen demand
CPO	Crude palm oil, the primary product of an oil palm plantation or factory
CV	Coefficient of variation
D	<i>Dura</i> – thick-shelled fruit form
DCF	Discounted cash flow
DM/WM	Ratio of dry weight to fresh weight of mesocarp
DMP	Dry matter production
DNA	Deoxyribonucleic acid
DRIS	Diagnosis and Recommendation Integrated System (see Sections 11.4.3, 11.6.4)
DxP	<i>Dura</i> × <i>pisifera</i> cross, or <i>tenera</i> (see Section 2.2.2.6)
<i>e</i>	radiation use efficiency (dry matter produced per unit radiation intercepted)
Ea	Actual evapotranspiration
Ec	Crop potential evapotranspiration
EFB	Empty fruit bunches – the bunch stalks remaining after fruit stripping
EIA	Environmental impact assessment

Eo	Potential evapotranspiration
f	Fraction of total solar radiation absorbed by the foliage
FAO	Food and Agriculture Organisation of the United Nations
F/B	Fruit to bunch ratio, by weight
FELDA	Federal Land Development Authority (Malaysia)
FFA	Free fatty acids
FFB	Fresh fruit bunches
FIS	Family and individual selection (see Section 5.4.2.2)
GCA	General combining ability (see Section 5.2.6)
GIS	Geographic information system
GMO	Genetically modified organism (produced by DNA transformation)
GPS	Global positioning system
GxE	Genotype $\times$ environment interaction
H	Harvest index (proportion of total dry matter in harvested product)
h_b^2	Heritability, broad sense (see Section 5.2.6.2)
h_n^2	Heritability, narrow sense (see Section 5.2.6.2)
INEAC	Institut National pour l'Etude Agronomique du Congo Belge
INFERS	Integrated site-specific fertiliser recommendation system (see Section 11.6.2)
IOPRI	Indonesian Oil Palm Research Institute
IPM	Integrated pest management
IRHO	Institut pour Recherche sur les Huiles et Oléagineux
IV	Iodine value – a measure of unsaturation in an oil or fat
K	Potassium
K/B	Kernel to bunch ratio, normally measured in a bunch analysis laboratory
KER	Kernel extraction rate, as measured in the factory
K/F	Kernel to fruit ratio
L	Leaf area index (ratio of total leaf area to ground area)
LAR	Leaf area ratio (ratio of leaf area to leaf weight)
LSI	Land suitability index
MARDI	Malaysian Agricultural Research and Development Institute
M/F	Mesocarp to fruit ratio (also WM/F)
Mg	Magnesium
MPa	Megapascal
MPOA	Malaysian Palm Oil Association
MPOB	Malaysian Palm Oil Board
MRS	Minimum ripeness standard
N	Nitrogen
NAA	α -Naphthalene acetic acid
NAR	Net assimilation rate
NIFOR	Nigerian Institute for Oil Palm Research
ns	Not significant
O/B	Oil to bunch ratio, normally measured in a bunch analysis laboratory
O/DM	Oil to dry mesocarp ratio
OER	Oil extraction rate, as measured in the factory
OPGL	Oil Palm Genetics Laboratory (Malaysia)
O/WM	Oil to wet mesocarp ratio (also O/M)
P	<i>Pisifera</i> – Shell-less fruit form
P	Phosphorus
P	Petiole cross-sectional area (see Section 4.1.3.2)
PAR	Photosynthetically active radiation
PKO	Palm kernel oil
PNG	Papua New Guinea

POME	Palm oil mill effluent – combined effluents from steriliser and centrifuges
PORIM	Palm Oil Research Institute of Malaysia (now Malaysian Palm Oil Board)
ppm	Parts per million
PV	Peroxide value
PWD	Potential water deficit
r	Correlation coefficient
R	Coefficient of multiple correlation (R^2 = proportion of variation explained by regression)
RFLP	Restriction fragment length polymorphism (see Section 5.2.8.1)
RGR	Relative growth rate
RISPA	Research Institute of the Sumatran Planters' Association
RM	Malaysian Ringgit (RM3.8 = US\$ 1 in 2002)
RRS	Reciprocal recurrent selection (see Section 5.4.2.1)
S	Total solar radiation, per unit area and time
SCA	Specific combining ability (see Section 5.2.6)
S/F	Shell to fruit ratio
SIRIM	Standards and Industrial Research Institute of Malaysia
SWD	Soil water deficit
SYP	Site yield potential (see also ASYP)
t	Metric ton (tonne)
T	<i>Tenera</i> – thin shelled fruit form
TLC	Total leaf cations
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UV	Ultra-violet
VDM	Vegetative dry matter
VPD	Vapour pressure deficit
WAIFOR	West African Institute for Oil Palm Research
WM/F	Wet mesocarp to fruit ratio
*	Significant at 5% probability level
**	Significant at 1% probability level
***	Significant at 0.1% probability level

Chapter 1

The Origin and Development of the Oil Palm Industry

1.1 ORIGIN OF THE OIL PALM

The oil palm gives the highest yields per hectare of all oil crops at present. The fruit of the palm is a central hard-shelled nut surrounded by an outer pulp (mesocarp) which contains the normal palm oil of commerce. The nut contains the palm kernel, from which a different type of oil, palm kernel oil, is extracted by pressing, leaving a proteinaceous residue that is a valuable animal feed, palm kernel cake. The high and increasing yields of the oil palm have led to a rapidly expanding world industry, now based in the tropical areas of Asia, Africa and America. Its origin is believed to have been in Africa, but the most productive parts of the industry at present are in Malaysia and Indonesia, which provide most of the oil entering international trade.

1.1.1 Physical evidence

At present the palm exists in a wild, semi-wild and cultivated state in three main areas of the equatorial tropics: Africa, South-east Asia and South and Central America, but a great deal of this spread has been a result of its domestication by man. There is fossil, historical and linguistic evidence for an African origin of the oil palm. Fat found in a tomb at Abydos in Egypt from 5000 BP may have been palm oil, but this is very uncertain (Raymond, 1961). Botanical evidence of the American origin of related genera suggests an origin in South America, and there are wild palm groves in Brazil as well as in Africa. There has been a long-running controversy on this point (Cook, 1942) and it has been suggested that the oil palm was transported to Africa in pre-Colombian times (Corner, 1966). However, direct evidence of an African origin has accumulated over recent decades by the dating of pollen in sediments.

Pollen similar to that of the oil palm has been extracted by Zeven (1964) from Miocene sediments in Nigeria. Elenga *et al.* (1994) reported oil palm pollen in two deep cores taken in the Congo, which covered the

period since 24,000 years BP. The climate became more humid from 13,000 BP and pollen of *Elais guineensis* was found more and more frequently from 2850 to 2750 BP onwards. The authors suggested that this was caused by increasing human populations, which were already using the oil palm for food. Raynaud *et al.* (1996) also found pollen in lake sediment cores from the south-west Cameroons, which covered the period after 2730 BP, when many pioneer species started to appear. Ergo (1996) found fossilised seeds of oil palm in Uganda, and considered that this proved the African origin of the oil palm. Sowunmi (1999) discovered oil palm nut shells in a rainforest site, and suggested that a sharp increase in late Holocene times, around 5000 BP, indicated the start of cultivation of the palm. A different theory concerning the distribution of the palm in central Africa was presented by Maley (1999) and Maley and Chepstow-Lusty (2001), who considered that the expansion of the palm groves arose following a decline of forests in many areas due to a widespread drier phase in the climate around 2500–2800 BP, which was reversed later, perhaps around 2000 BP. The palm then acted as a pioneer species as the forest re-expanded into surrounding areas, so the groves are natural populations. This expansion may be true, but the historical association of the palm with human habitation and farming is so close that it is difficult to accept Maley and Chepstow-Lusty's (2001) theory as the whole story. There seems little doubt that the human population functioned as a seed distributor for and user of the oil palm, although people did not 'cultivate' it in the sense of planting it. The physical evidence for the African origin of the oil palm is therefore very strong. The evidence for human use of the oil palm from several thousand years ago is not quite so strong, but still seems convincing.

1.1.2 Historical evidence

The historical record about the oil palm is meagre, and it is only relatively recently that this has been related to

the main journeys and the records of exploration in Africa (Rees, 1965a; Zeven, 1965). Portuguese exploration and trade on the west African coast began in 1434, with the Dutch and English first arriving and starting to explore some 150 years later. The first record of what may be the oil palm is that of Ca' da Mosto (1435–1460) (Crone, 1937), who wrote that 'There is to be found in this country a species of tree bearing red nuts with black eyes in great quantity, but they are small'. Of an oil used for food he wrote '[It] has three properties, the scent of violets, the taste of our olive oil and a colour which tinges the food like saffron, but is more attractive.' Duarte Pacheco Pereira mentions palm groves near Liberia, from his voyage of 1506–1508, and trade in palm oil (*azeite de palma*) near Forcados in Nigeria. Later accounts also mention palm wine. Other early authors refer to oil palms or palm oil as something originating from West Africa (Opsomer, 1956), but there are no such early reports of oil palms in the literature of Brazilian exploration. There is also considerable linguistic evidence that Brazilian terms describing oil palms are of African origin (Hartley, 1988).

1.1.3 Natural habitat

The difficulty of assigning a natural, original habitat is that the palm does not normally grow in the primary forest or the savannah, but it flourishes when humans start to fell the forest, settle there and use the oil palm. The felling of trees allows the palm to act as a pioneer species, and its seed may be spread by animals such as rodents, and by some bird species. However, it is likely that the main agency spreading the oil palm is man when he uses oil palm products. Deliberately or by accident, humans spread seeds within their home area, so that a large number of semi-domesticated palms grow up around their homes or along their pathways. The system of shifting cultivation led to a gradual movement of a village through the surrounding forest, thus ensuring even wider spread of the palm. These spread mechanisms are believed to be responsible for the palm groves of Africa, which were well established at the time of the European explorations. The palm groves of Brazil have presumably been formed by a similar process.

Various suggestions have been made about the original habitat of the oil palm, before the rapid spread indicated by the pollen evidence (Section 1.1.1) that has been interpreted as showing the early domestication of the palm. Chevalier (1934) suggested that the origin was in forest outliers close to rivers (*galeries forestiers*), probably in association with the *Raphia* palm. The forest in such habitat is insufficiently high or dense to

shade the palms out, and the water supply will normally be excellent. Chevalier (1934) considered that such forest fringes along rivers could be found virtually throughout Africa, and palms are still often found in such situations. In Sumatra and Malaysia similar habitats have been colonised by 'escaped' oil palms. The freshwater swamp has been suggested as an alternative by Waterston (1953), but the distinction between this and the previous suggestion is not very clear. The oil palm does not tolerate either saline conditions or fresh but stagnant water above the soil surface, but it accepts fluctuating freshwater tables, water tables 50 cm or more below the soil surface, and moving soil water in light-textured soils and sediments. It is certainly resistant to relatively high water tables in hydromorphic soils, as shown by the many plantations in low-lying areas, and there are good reasons for assuming that its original habitat was of this type.

1.2 THE OIL PALM IN AFRICA

1.2.1 Geographical distribution

From the above discussion it is clear that the oil palm could spread widely where the climate was acceptable and there was human farming activity. Some movement of seed may have been due to other species, but humans are clearly by far the most important in this regard.

The most recent description of the distribution was that by Zeven (1967), following that by Schad (1914) (Fig. 1.1). Starting from the northernmost occurrences along the west African coast, the first concentration of palms is in the highlands of the Fouta Djallon district of Guinea, at 10–11°N. The palm belt of Africa then runs through Sierra Leone, Liberia, the Ivory Coast, Ghana, Togoland, Benin (previously Dahomey), Nigeria, the Cameroons, the People's Republic of Congo and the Democratic Republic of Congo (formerly Zaïre). In west Africa the belt is narrow, because of the rapid decline in rainfall northwards, but in equatorial Africa it is more diffuse. Thus, in Nigeria there are no semi-wild palms north of about 7°N, except in particularly favoured areas where there are shallow water tables, such as near the Jos plateau.

In central Africa oil palms grow through much of the Congo region and even into Angola. Most are between 3°N and 7°S, but sparse palms can be found as far south as 15°S. Further east, stands of semi-wild palms are found on the Congo–Uganda border, between Lake Kivu and Lake Tanganyika, on the eastern shore of the latter, and scattered along the coast. Most of eastern

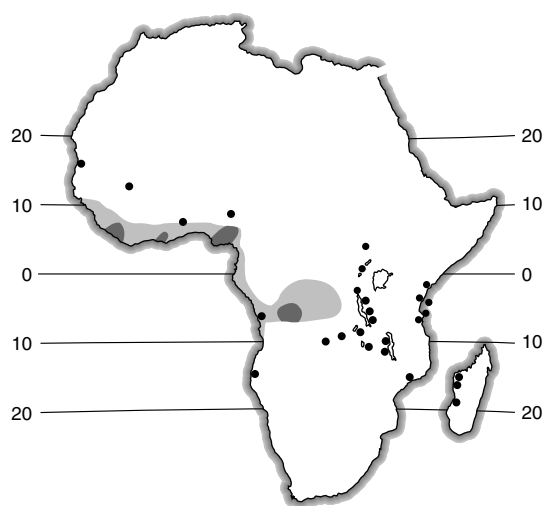


Fig. 1.1 Distribution of the oil palm in Africa. Cross-hatched areas are the main West African oil palm belt. Double-hatching indicates areas of highest population of people and of oil palm. Black dots are positions of isolated colonies of oil palms. (After Hartley, 1988.)

Africa is unsuitable for oil palms because it is too dry or lies at too high an altitude, or both. This very wide distribution, in a region that is only suitable for the palm in limited areas, suggests that palm fruit has been transported widely and regularly by human agency, perhaps in connection with the Arab slave trade.

The oil palm is also found on the island of Madagascar, and reaches remarkably far south, at 21°S. It occurs mainly on the west coast, whereas the local climate appears most favourable on the east. This suggests that the palm was brought by early migrants.

Apart from the rainfall, altitude is the greatest barrier to oil palm establishment, and normally the palm is not grown above 300 m or so. However, where rainfall is sufficient, it grows at up to 1300 m on the Cameroon mountain, and at up to 1000 m on the Fouta Djallon in Guinea, the East Cameroons and in many localities in East Africa, although the yields tend to be low (see Section 3.2.4). The development of palms that are tolerant of higher altitudes is now proceeding (5.3.6.2).

1.2.2 African palm groves

Before the early twentieth century the only trade sources of oil palm products were the large semi-wild groves of Africa, and to a smaller extent the similar groves of Brazil. Produce from the latter never entered

international trade but was used locally. In Africa there was also a large local consumption, but with a large exportable surplus of oil, and especially of kernels from the groves.

The essential interaction between humans and the oil palm is supported by the fact that the palm groves were densest where the human population was largest, as in south-eastern Nigeria. There, the practice of shifting cultivation (Nye and Greenland, 1960) was so intense that the forest fallow period was a very few years, so few trees of any height grew up, and as the palms were protected and unshaded, they yielded relatively well and formed productive groves (Andah, 1993). In less densely populated areas, where the pressures on the land were less, the forest might reach 20 m or more before being felled for another spell of cropping. Oil palms were therefore suppressed unless they were very tall, and while a few palms would always persist in such circumstances, dense groves never developed. When the trees were felled for another period of cultivation the existing palms were no longer shaded and started to fruit again, and a few new seedling palms were established. However, such conditions did not produce yields on which a large international trade could be based. These palms, with 'home garden' palms or those on the edge of settlements, would supply local needs for oil and palm wine, and the leaves would be used for palm thatch.

Where local needs used up most of the palm oil, the kernels were still available for trade. As there was for a long time no local crushing industry, the palm kernels formed a separate large export trade. Later, African countries developing crushing plants, and by 1972 African countries were exporting around 100,000 t of palm kernel oil annually.

1.2.3 Early trade

From the above it is clear that the oil palm industry was very largely centred on Africa until the time of World War II. The origin of the trade is an interesting story. The Portuguese founded a fort at Elmina in Ghana in 1482, and reached Benin City in southern Nigeria in 1492, but the commercial opportunities were small compared with those in South America or the Spice Islands in present-day Indonesia, and the Portuguese interest remained fairly small. Nevertheless, other countries also built forts and settlements along the coast, especially after the West African slave trade started in 1562. The trade diminished greatly after 1807, when the slave trade was banned in British possessions and ships. During the whole of this time palm oil was used in international trade only as food for the slaves.

After 1807 the slave trade became progressively more risky and alternative commerce developed, in which ivory and timber were then the most important commodities. In 1790 less than 130 t of palm oil was imported to England. There was virtually no knowledge of it or of its uses, or even an accepted name for it in English until 1804. Trade restrictions, the small number of traders, the serious danger of disease, the lack of access to the interior for the European traders, and the continuing illegal, but profitable, traffic in slaves to South America prevented any major developments.

A fluctuating level of trade continued until the 1830s. After that the British Government deliberately encouraged the oil palm trade (Stilliard, 1938), although a decreasing illegal slave trade to the Americas continued until the palm oil trade finally took off in the 1850s. Palm oil was exported from the Benue River, from Bonny and from the Calabar River in growing amounts, the whole area becoming known as the Oil Rivers (Stilliard, 1938; Dike, 1956). The final demise of the slave trade was in large measure due to the fact that there was a profitable and thriving alternative trade immediately available.

The early trade was conducted by traders from their ships, because of the great danger of disease on the West African coast and the uncertainties of living on the land. The control of all trade on land lay wholly with local chiefs and middlemen in the ports, and the quality of oil was therefore very variable. Later land-based expatriate trading posts were established after a British Consul was appointed for the Oil Rivers Protectorate. The trade was around 12,000 t/year in the 1830s, but reached 30,000 t in the 1860s and 87,000 t by 1911.

This growth was partly due to improved communications and security in southern Nigeria, where the oil palm trade was profitable to farmers, who responded actively to good prices by increasing the supply of oil (Njoku, 1983). It was also due to economic development and new inventions in northern countries, which greatly increased the demand for the oil. Palm oil was wanted for soap, candles, margarine, lubricants for machinery and industrial processes. Prices in the 1860s were around £40/t, in real terms far higher than the present world price (Dike, 1956).

The demand for palm kernel oil also increased sharply. Exports of kernels started in 1832, the kernels being produced by African women who cracked the nuts one by one. The trade rose rapidly, so that by 1905 157,000 t of kernels were exported by British territories in West Africa, and by 1911 this had reached 232,000 t valued at £3,400,000. The quantities of kernels were much larger than those of oil, relative to the production

of the palms, probably because of the large local consumption of the latter. The export of both oil and kernels increased gradually to a maximum before and after World War II, during which demand was extremely high, but it declined gradually in the decades afterwards. (For further details see Hartley, 1988.)

Gerritsma and Wessel (1997) covered much the same historical ground as above, but told from the point of view of the highly successful domestication of a wild plant, a process that they consider is still continuing in terms of increasing yield and more sustainable methods of establishment and cultivation. Here, the word 'domestication' is used in a rather unusual way, because all the main crops that have been farmed for millennia are still giving increasing yields today, although there is no doubt that they have been 'domesticated' for a very long time indeed.

Henderson and Osborne (2000) provided a very interesting review of the relationship of the oil palm trade to the developing Industrial Revolution during the nineteenth century. The first importation was 32 barrels of oil in 1590, and soap was made from it as early as 1589. Its main use came 200 years later, when by the 1830s almost all soap made in Britain was from palm oil. A little later in the century it became normal to use it for candles, composed largely of palmitic acid, although they were called 'stearic candles'. In extreme situations these can also be used as food. At one time palm oil was used to produce lighting gas. By the middle of the nineteenth century new uses were being invented rapidly, including as lubricants on the railways and as a flux in the tin-plate industry, which grew on the need for canned foods. Later, margarine was developed, producing another large demand. Glycerol (glycerine) from palm oil had numerous uses of its own. Henderson and Osborne (2000) support the case that it was this explosion of demand for palm oil that really ended the slave trade in West Africa, as local chiefs found it more profitable to export the oil.

1.2.4 Development, use and improvement of the African palm groves

The West African and Brazilian groves were thus collections of palms of varying ages randomly scattered over an area in which shifting cultivation was the predominant agricultural system. The increase in density of palms follows the increasing density of the human population, but the yield is always meagre compared with that from plantation palms, apart from occasional very productive palms in particularly favourable locations. Palms in household compounds or home gardens will tend to be productive because of the return of domestic

Table 1.1 Mean number of palms per hectare, and yield of fruit bunches in each of four subtypes of thinned grove near Asutan Ekpe, Nigeria, in 1949–1951

Grove type	Number of palms/ha			Yield of fruit bunches (t/ha per annum)
	Smooth- stemmed	Rough- stemmed	Total	
Dense groves	94	106	200	3.07
Degraded groves with farmland palms	86	62	148	2.55
Farmland	57	35	92	1.55
Groves around compounds in farmland	52	62	114	1.91

After Hartley (1988).

and garden refuse to the soil. The most productive palms are those that grow to a height where the crowns can receive full sunlight. The harvesting of these is often arduous and dangerous, being done by climbing, with one or two ropes around the palm and the climber. Climbing the older and taller palms is not an attractive task. It is often difficult to determine from the ground whether bunches on such tall palms are ripe, and this causes poor quality of oil due to harvesting of overripe fruit (see Section 10.4.3).

The groves of palms are contributing a steadily decreasing fraction of world trade in palm products, and Nigeria now actually imports oil to meet domestic requirements (Section 1.4.3.4). However, they still form a very interesting and unique agricultural ecosystem, and the various subgroups of grove are briefly noted here (Zeven, 1965, 1967, 1968, 1972). The Brazilian groves in the state of Bahia were established by the same processes, and are very similar to those in south-east Nigeria. They are classified as follows, based on the palm and tree density.

- Secondary forest with a few oil palms. The yield is very low, an example in mid-western Nigeria being 1500 kg fresh fruit bunch (FFB)/ha, because of the low palm density and the shading by overhanging trees. Palms grow very slowly for the same reason, unless they can break through the canopy.
- Palm bush. These contain 75–150 palms with trunks/ha, and yields are over 2000 kg FFB/ha. Farming is relatively frequent.
- Dense grove and farmland palms. These are typical of south-eastern Nigeria, where a high population density has led to an almost pure stand of palms, with some small shrubs and occasional trees, and arable crops.
- Thinned grove. In some cases the farmers deliberately thin out dense palms to allow in more light and achieve higher yields of food crops.

Table 1.2 Oil palm area (ha), FFB (t), palm oil (t) and yield (t/ha) in Nigeria, by production system and ownership

Production system	('000)			
	Area (ha)	FFB (t)	Palm oil (t)	Yield (t/ha)
Wild grove	2,100	6,300	630	0.3
Estate	95	950	180	1.9
Smallholders	150	1,200	150	1.0
Total	2,345	8,450	960	0.4

Omoti (pers. comm., 2000).

- Sparse groves. As thinning out of palms, frequent arable cropping and exhaustion of the soil become more extreme, the area becomes sparse grove with perhaps only 40 palms/ha. Further degradation of the soil and vegetation leads to derived savannah with a few isolated clumps of palms.

Some typical values of the productivity of thinned grove types are given in Table 1.1, showing that the yield levels are pitifully small by modern plantation standards. As a contrast, average yields of FFB are 15 t/ha in the Ivory Coast, and 20–30 t/ha in Malaysia and Indonesia. Methods of improving (rehabilitating) the groves have frequently been suggested and tested, and are still being considered (Section 1.4.3.4). However, the problems of organisation and ownership, and the need for investment in fertiliser, have usually prevented any useful practical success with these unselected and poorly treated grove palms, the productivity of which is intrinsically small (Sparnaaij, 1958). Improved palms planted under the old ones grow extremely slowly. The decrease in the commercial value of the groves has reduced the interest in such research (Hartley, 1988). However, the Nigerian groves still dominate Nigerian production of palm oil for local consumption (Table 1.2).

1.3 DEVELOPMENT OF THE OIL PALM PLANTATION INDUSTRY

1.3.1 The African plantation industry

Early plantings were made in the Belgian Congo, various French territories and in Nigeria before or shortly after World War I. Recommendations to encourage plantations in British West Africa were made, but nothing was done. Lord Leverhulme tried to obtain concessions to set up plantations and build mills in Sierra Leone and Ghana, but these failed owing to opposition from both the government and the local people. There was much more activity in the Congo, with various developments during the 1920s, including encouraging the planting of palms by local farmers. In the then Belgian Congo concessions were also granted to the Leverhulme interests, and these were successful, with extensive plantations and several palm oil mills. These also took fruit from local farmers and smallholders who planted their own palms. These initiatives led to a rapid increase in the exports of palm oil and kernels, which were 56,000 and 64,000 t, respectively, in 1935. (Further detailed information about this early period can be found in Hartley, 1988.) The scientific relationship between the thick-shelled *dura* and the more desirable *tenera* palms was first elucidated in the Congo (5.1.5), which gave a great impetus to the plantation developments there, and later to the whole world oil palm industry. Later political changes and intermittent violence damaged the Congolese industry greatly. The most successful African plantations in the latter part of the twentieth century were in the Ivory Coast underpinned by excellent research supported from France.

1.3.2 The Deli palm

Good management, with improved planting material, regular fertilising, maintenance and harvesting are essential to produce high yields and high quality. Whereas many farmers maintain their plots well, the average standard will almost always be below that of plantations with professional managers, which are run as industries rather than as farms. The establishment of oil palm plantations started in South-east Asia, with little or no direct connection between the existing West African groves and this new industry. As noted above, attempts to set up plantations in Africa had mixed early success, and later were overtaken by political volatility and state failure, although there is no doubt that successful plantations can be operated in the climatically more suitable areas.

The earliest record of the introduction of oil palms into South-east Asia was of four seedlings planted in

the Buitenzorg (now Bogor) Botanic Gardens in 1848 in Java in the then Dutch East Indies. Two of these were from the Amsterdam Botanic gardens, but it is not known how they originated. The other two were from 'Bourbon or Mauritius' in the Indian Ocean, Bourbon being on Reunion. The palms that sprang from these four seedlings were all quite similar, and it has been supposed that they were all originally produced in Amsterdam, from seeds brought from Africa (see Hartley, 1988; Gerritsma and Wessell, 1997; Pamin, 1998). The uniformity of the progeny suggests that all four seedlings may well have originated from a single parent palm. After transfer of the progeny of these palms to Sumatra in 1875, they became the foundation stock for the South-east Asian industry. They had the following characteristics in common. The fruit is *dura* (thick-shelled) (Section 5.1.1.1) but the spikelets of the bunches end in short spikes rather than long spines as found in African *duras*. The fruit are large and contain much more oil-bearing mesocarp (60%) than the normal African *dura*, although the oil percentage is a little lower and the fruit is paler in colour.

Pamin (1998) has described the early years in Indonesia in some detail. The seeds from the four palms initially planted at Bogor were distributed widely. They were originally used as a decorative plant, and it was a number of years before their commercial possibilities were properly exploited. However, experimental plots were established as early as 1860, and the description by Pamin (1998) certainly suggests that the possibility of economic exploitation of the palm was kept in view right from the initial introduction. One of these plots was at Deli in Sumatra, and from this the entire stock has been named the 'Deli palm'. The main reason for the lack of large-scale economic use for over 60 years from the first introduction was probably uncertainty about the efficiency of large-scale extraction methods, and consequently about the economic return that could be expected (see Section 13.4). The rapidly increasing market for the oil towards the end of the nineteenth century (Section 1.2.3) must also have been a great incentive for seeking a more efficient production system than the African groves.

1.3.3 The Asian plantation industry

The first large plantation in Sumatra was planted in 1911, using Deli palms. It was recognised that the Deli palms were more productive than African palms, both in terms of fruit bunches, and in their having a larger percentage of oil to bunch because of the better fruit composition and larger fraction of mesocarp. By 1917 the first true plantation was established in Malaysia in

the Selangor district. Subsequently, the Sumatran industry forged ahead rapidly, with 31,600 ha planted by 1925, when Malaysia only had 3350 ha. By 1938, before World War II, the areas were respectively 92,000 and 20,000 ha, the plantation industry was fully established, and it was producing more oil than the African industry. The extraction problem had been largely solved, with both centrifuge and press machinery operating in large mills. World War II and subsequent disturbances set the whole industry back a long way.

1.4 WORLD-WIDE DEVELOPMENT OF THE INDUSTRY, 1950–2001

1.4.1 General

The world production of oil palm products has always been impossible to assess accurately owing to the quantities of produce that are not recorded, because they are produced in groves, smallholder plots and farms, and used for the farmer's domestic purposes or sold locally. Estimates suggest that world-wide production rose from 2.2 million tonnes of palm oil and 1.2 million tonnes of kernels in 1972 to 21 million tonnes of oil, 6 million tonnes of kernels and 2.6 million tonnes of kernel oil in 2000 (Oil World, 2000, Table 1.3). Most of this increase can be attributed to Malaysia and Indonesia, and to some smaller Asian producers. The production of palm oil has now overtaken that of other vegetable oils, apart from soybean oil.

The Asian industry had to make a fresh start after World War II. The Malaysian industry rapidly became a major supporter of that country's economy. Ownership of the plantations was originally in the hands of British companies, but it has been largely repatriated to Malaysia; recently a considerable amount of foreign

capital has been invested in the Indonesian industry, much of it from Malaysia. The largest changes have been due to the shift from Deli *dura* palms to *tenera* palms, although the genetic basis of the industry is still remarkably narrow, and the great debt to the Deli *dura* remains (see Chapter 5). The amounts exported and the prices are shown from the start of records up to the present in Tables 1.4 and 1.5.

This long sequence of export data allows the changing trends in the international industry to be seen easily. The most striking effect has been the shrinkage of the African part of the international trade, which has by now almost disappeared in many countries. Over the same period Malaysia and Indonesia have become dominant in the trade, and have built up an enormous basis of experience, both in the actual production of palm oil and palm kernel oil, and in the ancillary upstream and downstream industries such as plant breeding, agricultural machinery and agrochemicals, plant tissue culture, oil fractionation and oleochemicals. They now also have very efficient supply chains and the reputation of reliable partners in trade. The main reason for the shrinkage of the trade in kernels is that these are now very largely crushed in their country of origin. The smaller tropical Asian countries are gradually following the route pioneered by these two countries.

The Deli oil palm was first recognised in Indonesia, wherever it may have come from, and the plantation development started there. However, World War II and the following independence struggle in Indonesia meant that Malaysia leapt forward in comparison, despite the communist emergency between 1948 and 1957, and by 1970 it was well ahead in total planted area. From that point the Malaysian oil palm area grew in a roughly linear fashion (Fig. 1.2) (Mielke, 1998) until the end of the twentieth century. By contrast, Indonesian production grew relatively slowly until the

Table 1.3 World production of selected oils and fats (million tonnes) including predicted productions up to 2020

Year	Palm oil	Palm kernel oil	Soya bean oil	Sunflower oil	Rapeseed oil	Other vegetable oils	Animal oils and fats	Total
1960	1.26	0.42	3.33	1.79	1.10	8.95	11.18	28.03
1970	1.74	0.38	6.48	3.49	1.83	10.01	14.46	38.39
1980	4.55	0.64	13.32	5.04	3.53	11.17	18.26	56.51
1990	11.01	1.45	16.10	7.87	8.16	15.02	20.20	79.81
2000	21.12	2.64	25.21	9.6	14.4	17.17	21.57	111.71
2010 ^a	29.79	3.87	28.16	12.98	23.65	20.69	22.94	142.08
2020 ^a	35.69	4.64	34.31	15.86	34.79	25.01	24.00	174.30

^aForecast.

After Jalani (1998).

Table 1.4 Exports of palm oil and palm kernels (thousand tonnes/annum) from various countries with large production levels

(a) Exports of palm oil, 1909–1985

Country	1909–1913	1924–1931	1932–1939	1940–1945	1946–1953	1954–1961	1962–1969	1970–1977	1978–1981	1982–1985
Angola	2	4	4	5	12	11	15	11	–	–
Benin	13	15	18	8	9	14	11	7	4	3
Congo	2	25	58	74	119	158	124	71	7	8
Indonesia	–	28	161	82	77	122	140	294	366	376
Ivory Coast	6	7	18	8	9	14	1	67	71	57
Malaysia	–	2	31	26	46	73	188	887	2,042	2,996
Nigeria	83	126	132	132	156	180	81	9	–	–
PNG	–	–	–	–	–	–	–	10	35	104
Sierra Leone	9	4	3	1	2	–	–	–	–	–

(b) Exports of palm oil, 1984–2001

Country	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Brazil	5	8	–	3	5	5	2	1	8	11	13	20	31	30	26	14	31	29
Cameroon	5	7	18	27	18	30	26	7	25	24	29	8	36	13	15	14	16	16
Colombia	–	–	–	–	–	–	3	3	8	3	20	19	25	61	70	90	97	90
Costa Rica	–	–	–	–	9	8	17	12	22	31	37	42	56	71	72	80	96	78
Ecuador	–	–	–	–	–	–	–	2	9	12	9	19	22	15	15	64	25	32
Indonesia	247	652	709	734	920	991	1,163	1,628	1,304	1,719	2,173	1,856	1,851	2,982	2,002	3,319	4,140	4,940
Ivory Coast	53	56	105	110	61	76	156	151	143	170	148	120	99	73	102	101	72	75
Malaysia	2,978	3,286	4,558	4,261	4,348	5,213	5,949	5,769	5,801	6,265	6,895	6,643	7,230	7,747	7,748	9,235	9,280	10,733
PNG	130	123	129	123	103	133	143	166	178	246	231	220	267	275	213	254	336	328
Thailand	5	13	8	9	1	1	–	1	2	–	18	16	8	67	32	65	87	180

(c) Exports of palm kernels, 1909–1985

Country	1909–1913	1924–1931	1932–1939	1940–1945	1946–1953	1954–1961	1962–1969	1970–1977	1978–1981	1982–1985
Angola	6	7	6	7	12	10	15	6	–	–
Benin	35	40	73	49	67	52	24	4	–	–
Congo	7	72	72	46	77	39	4	–	–	–
Indonesia	–	2	34	8	22	37	36	38	24	11
Ivory Coast	6	12	73	49	67	52	11	25	9	7
Liberia	–	–	–	4	14	12	12	4	–	–
Malaysia	–	–	6	3	8	18	26	22	26	45
Nigeria	175	260	318	319	360	439	313	199	90	41
Sierra Leone	48	67	74	43	69	59	27	35	10	10

(d) Exports of palm kernels, 1984–2001

Country	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Cameroon	15	5	2	5	3	–	2	3	2	3	1	–	5	–	–	–	–	–
Guinea Bissau	7	2	8	5	6	5	2	5	3	2	3	1	1	1	2	2	2	2
Indonesia	9	23	4	1	–	–	–	1	–	–	1	–	1	1	1	–	–	–
Ivory Coast	14	–	–	–	1	10	10	8	3	1	5	1	4	2	–	1	1	1
Malaysia	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Nigeria	42	32	72	92	103	64	37	23	13	8	5	2	9	1	8	8	9	6
PNG	14	17	18	19	11	8	11	17	21	17	22	19	21	26	8	1	1	1
Solomon Islands	4	4	3	2	3	4	5	5	4	7	6	7	6	6	7	7	7	7

(e) Exports of palm kernel oil, 1940–1985

Country	1940–1945	1946–1953	1954–1961	1962–1969	1970–1977	1978–1981	1982–1985
Angola	–	–	–	2	1	–	–
Benin	–	–	–	12	16	8	8
Congo	2	14	48	41	36	18	15
Indonesia	–	–	–	–	8	4	26
Ivory Coast	–	–	–	–	2	9	14
Malaysia	–	–	–	–	69	199	380
Nigeria	–	–	–	17	28	40	24

(f) Exports of palm kernel oil, 1984–2001

Country	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Benin	9	4	8	5	3	4	1	2	3	2	4	5	4	4	4	4	5	4
Congo	13	15	13	7	9	5	3	1	3	3	3	7	5	4	3	2	1	1
Costa Rica	–	–	–	–	–	–	–	–	4	5	5	6	6	6	6	6	6	6
Colombia	–	–	–	–	–	–	–	–	1	–	–	2	6	5	6	13	19	18
Indonesia	15	98	42	87	122	135	158	136	223	275	341	311	341	503	413	598	579	582
Ivory Coast	12	12	17	17	12	7	13	15	23	14	15	16	12	15	18	23	14	8
Malaysia	391	432	555	506	536	661	673	629	452	555	470	410	497	426	502	572	492	616
Nigeria	10	9	8	8	9	1	–	14	20	17	20	3	32	33	3	3	4	–
PNG	1	–	–	3	4	7	7	8	8	11	12	11	17	16	31	25	28	30
Philippines	–	–	1	–	2	1	6	6	4	7	6	1	1	1	3	2	3	2
Thailand	–	2	–	–	–	–	–	–	–	–	–	–	–	–	5	9	30	65

(a, c, e) After Hartley (1988); (b, d, f) after Oil World (2000).

Table 1.5 Prices in pounds and dollars of palm oil, palm kernels, palm kernel oil, palm olein and palm stearin

(a) UK pounds per tonne

Year	Palm oil	Palm kernels	Palm kernel oil
1911	29	18	37
1919	85	38	91
1931	20	12	23
1945	41	–	48
1955	86	51	93
1959	89	69	133
1963/64	84	54	102
1965/66	91	60	111
1967/68	76	66	130
1969/70	74	69	141
1971/72	98	53	121
1973	155	107	187

(b) US dollars per tonne

Year	Palm oil	Palm kernels	Palm kernel oil	Palm olein	Palm stearin
1974	710	482	926		
1975	416	207	492		
1976	415	228	523		
1977	543	323	637		
1978	620	366	699		
1979	669	498	988		
1980	586	344	671		
1981	578	340	591	573	
1982	439	265	458	476	
1983	502	366	709	548	432
1984	729	532	1037	786	537
1985	501	291	551	543	402
1986	257	116	288	323	263
1987	343	114	426	390	349
1988	437	134	539	471	443
1989	350	127	472	375	348
1990	290	108	334	332	284
1991	339	125	417	393	294
1992	394	128	571	449	349
1993	378	109	437	434	370
1994	528	111	629	605	460
1995	628	117	677	685	568
1996	531	132	728	581	450
1997	546	91	652	605	466
1998	671	73	687	710	548
1999	436	71	694	491	358
2000	356	68	588	391	303

All values up to and including 1985 are from Hartley (1988, p. 26). Subsequent values are from Oil World Annual, with permission.

Palm oil: 1911–1945: Liverpool landed; 1955–1973: government selling price, 5% FFA; 1974–1985: Malaysian/Sumatran (resale) cif continent; 1986–2000 palm oil crude cif NW Europe.

Palm kernels: 1911–1973: Liverpool landed; 1974–1985: Nigerian cif Europe; palm kernel expeller 1986–2000: 21/23%, Malaysian cif Hamburg (to 1993) Rotterdam (after 1993).

Palm kernel oil: 1911–1973: government selling price, crude; 1974–2000: Malaysian cif Rotterdam.

Palm olein: 1981–2000 RBD Malaysian cif Rotterdam.

Palm stearin: 1983–2000: RBD Malaysian cif Rotterdam. (See Section 14.3.)

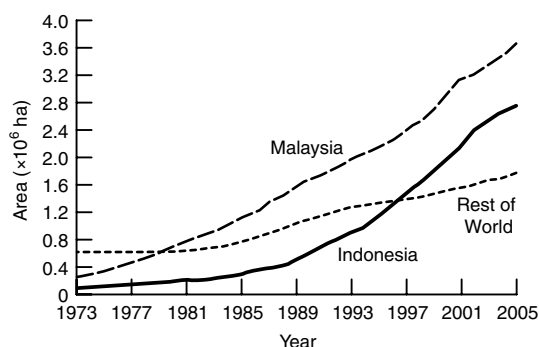


Fig. 1.2 Increase in mature oil palm area from 1973 to 2005, in Indonesia, Malaysia and the rest of the world. (Mielke, 2001, pers. comm.)

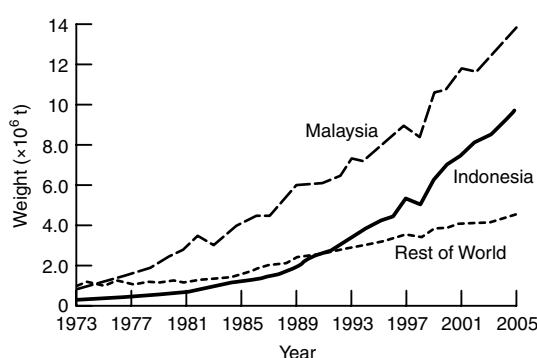


Fig. 1.3 Production of palm oil (million tonnes) from 1973 to 2005 in Indonesia, Malaysia and the rest of the world. (Mielke, 2001, pers. comm.)

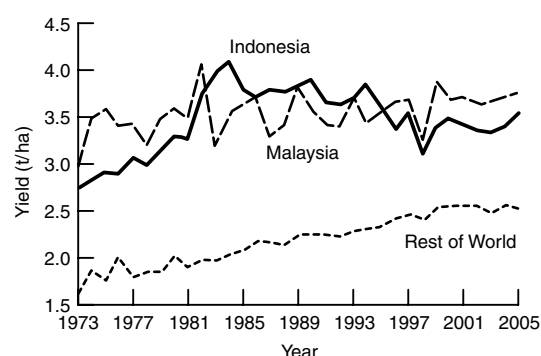


Fig. 1.4 Annual oil palm yields (t/ha) from 1973 to 2005 in Indonesia, Malaysia and the rest of the world. (Mielke, 2001, pers. comm.) Figures 1.2–1.4, from long range study 'Oil World 1976 to 2020' released 2002, by Oil World, Hamburg (info@oilworld.de).

late 1980s, but thereafter went into a phase of exponential growth (Fig. 1.3) (Mielke, 1998). This rapidly brought it to the same absolute rate of expansion as the Malaysian industry, although the relative rate of increase (in percent per year) was much larger. The yield per hectare of the Indonesian plantations caught up with the Malaysian level in about 1981, and remained roughly the same until the difficult years after 1997 (Fig. 1.4) (Mielke, 1998). Inspection of these graphs and Table 1.4 shows how completely dominant these two countries are over the rest of the world during this period, and probably will remain so for some time to come (Mielke, S., 1998, 2000; Mielke, T., 2000).

The Asian oil palm industry has thus developed at an astonishing rate, and now leads the world, whereas the African industry has gone backwards in most countries, with exceptions such as the Ivory Coast. The African industry still supplies a large part of the domestic demand for oil, and the large surplus of kernels has allowed these to continue as a substantial but declining export trade. The American oil palm industry has grown rather slowly, and has become established in many Central and South American countries (Table 1.4) but it is in some ways different to the others. Exports are rather small and a large part of the production is used locally. South America has several serious diseases of the oil palm that are not found elsewhere, and it has tended to develop through small to medium sized plantations, avoiding both the very large plantations of Asia and the wild palm culture of Africa. South American production will probably grow more rapidly in future, as will that of the remaining parts of equatorial south-east Asia (Philippines, Thailand, Papua New Guinea), but it must be some time before the joint dominance of Malaysia and Indonesia is seriously challenged.

The comparative growth of the production of most of the major vegetable oils is shown in Table 1.3 (Jalani, 1998). Oil palm production has caught up with soya bean oil, sunflower oil, and animal oils and fats. In the year 2000 soya bean oil was still ahead, and the projected production values for future years (Table 1.3) are so close that it is uncertain whether palm oil will in fact become the leading world vegetable oil soon. The production of a perennial plant cannot be changed as rapidly as that of an annual farm crop. The forecast figures suggest that palm oil will keep slightly ahead of soya bean oil, but the differences are trivial compared with the unavoidable errors of prediction. Stringfellow (1999) queried whether the oil palm was beginning to fall behind in the technological race with the other vegetable oils, and the oil palm industry must on no account become complacent (Section 1.5.4).

1.4.2 Price structures and competitiveness

1.4.2.1 Changes in the past

It is confusing to follow the fluctuations in commodity prices over short periods (Table 1.5), as they are notoriously difficult to predict or to explain. A clearer picture is presented by the real inflation-adjusted prices for oil products on the world markets over a long period (Fry, 1998) (Fig. 1.5a). Since 1950 there has been a clear, though varying, downward trend in the price for palm oil, which represents a mean 3% per annum decline (Table 1.6) (Fry, 1998). The corresponding figure for soya bean oil is 3.1% (Fig. 1.5b) (Fry, 1998), showing that palm oil is not alone in this price trend, which indeed affects all the major cereal crops also. Despite the rapidly growing world population, agricultural research and development has more than kept pace with it since World War II, leading to the decreasing prices for most major crops. The decline has been most rapid for the major vegetable oils.

The mean price trend was followed reasonably closely in the period 1950–1970. There followed the inflationary episode of the 1970s, which was at first seen as the beginning of a period of general raw material shortages (the ‘Club of Rome’ period). Prices also fluctuated after 1981, when the introduction of the weevil *Elaidobius kamerunicus* to the Far East produced a surge of production followed by a brief decline. Supplies rapidly recovered from these shocks, and the trend line was reached again by 1982. Following a below-trend period, roughly 1985–1995, an above-trend period followed in the late 1990s, but for most of 2000 and 2001 the price was US \$250, that is below the trend line. Indeed, a recovery to the trend line and above has recently given great relief to the industry with the price at about \$450/t. It is at present difficult to see any reason why this well-established downward trend of the real price should not continue, short of some global catastrophe, and this must be a major factor in the strategy of the industry in the next few decades (see Chapter 15) (Khalid Ibrahim, 1996).

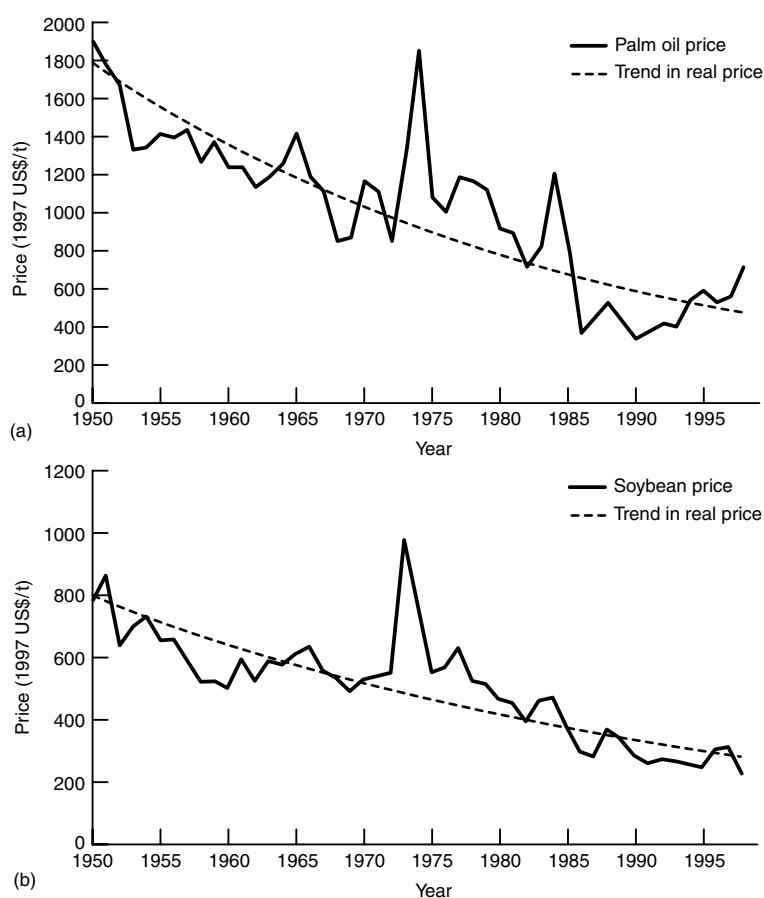


Fig. 1.5 Change over time in the real inflation-adjusted price of (a) palm oil and (b) soya bean oil. (After Fry, 1998; Tinker, 2000a.)

1.4.2.2 Future changes

The future demand and supply balance in the oil palm industry is not easy to foresee, because two trends will conflict. In the first trend, the demand is certain to continue increasing because of the expansion of population and wealth, and this may be read as a guarantee of a great future, as explained by Jalani (1998) (Table 1.7). This trend has changed the main markets for palm products greatly, with China, India and Pakistan becoming major importers and consumers (Mielke, 2001). Estimates of the increasing demand for foodstuffs in the next 30 years are usually expressed in terms of cereal demand, and this is expected to increase by

Table 1.6 Long-term inflation-adjusted rates of decline in the world market prices of various agricultural commodities, 1950–1995, per cent change per year

Commodity	Annual decline (%) 1950–1995
Sugar	1.5
Cocoa	1.9
Robusta coffee	1.9
Soya bean meal	2.1
Arabica coffee	2.1
Soya bean	2.2
Wheat	2.2
Maize	2.6
Rice	2.7
Coconut oil	2.9
Palm oil	3.0
Copra	3.0
Soya bean oil	3.1
Rubber	3.5

After Fry (1998).

roughly 50% by 2030 (Dyson, 1999; Pandya-Lorch *et al.*, 2001). The demand for fats and oils would be expected to increase proportionately more rapidly, and Mielke (2001) predicted that the demand for palm oil would double by 2020. However, this type of argument has been made for many years, with the suggestion that this must increase, or at least support, the world price. Despite this, the second and opposing trend is the steady secular decrease in the real price of palm oil described above. At present we have to regard palm oil as a commodity with no different niche markets (Jalani, 1998) except that palm kernel oil has some different uses, and the kernels produce cattle cake after pressing. All the other major oil crops (except for olive oil) are produced by crushing nuts. Particularly for soya bean, the main value of the product is in the presscake that is used for cattle concentrate feed, so that the sale of the oil gives only a secondary income. The crushers may therefore be able to sell the oil at very low prices if the protein feed price is high, and in general they have the advantages of a more diversified market. Basiron (2000) discussed strategies to sustain estates during periods of low prices, and noted the importance of early replanting.

1.4.2.3 Competition between regions

The above scenario is generally positive, though with some large question marks. However, a successful global industry does not guarantee success for each individual producer or country. The trend towards lower real prices will put pressure on countries with high costs per tonne of oil, which will depend closely on wage rates and yields per hectare. The structure of the perennial palm, and the way in which the palm bunch is presented on the tree, make it difficult to mechanise the harvesting operation. So, even as other processes are being mechanised rapidly in the Asian industry (see Sections 10.2

Table 1.7 World major producers of palm oil (million tonnes), with projections to 2020

Year	Malaysia	Indonesia	Thailand	Ivory Coast	Nigeria	Other Africa	Colombia	Other America	Others	Total
1980	2.6	0.7	0.02	0.1	0.4	0.2	0.07	0.06	0.3	4.5
1985	4.1	1.2	0.1	0.2	0.3	0.2	0.1	0.2	0.4	6.8
1990	6.1	2.4	0.2	0.3	0.6	0.3	0.2	0.3	0.6	11.0
1995	7.8	4.1	0.3	0.3	0.7	0.3	0.4	0.4	0.7	15.0
2000	10.0	7.0	0.4	0.4	0.8	0.4	0.4	0.5	1.0	20.9
2005 ^a	11.3	10.3	0.5	0.5	0.8	0.4	0.5	0.6	1.3	26.2
2010 ^a	12.6	12.4	0.6	0.5	0.9	0.5	0.6	0.7	1.6	30.4
2015 ^a	13.6	13.6	0.7	0.6	1.0	0.5	0.6	0.8	1.8	32.2
2020 ^a	14.9	15.1	0.8	0.7	1.1	0.5	0.7	0.9	1.9	36.6

^aForecast.

After Jalani (1998).

and 10.4.6), the likelihood is that oil palms will always demand a high labour input, and will never be able to compete with the low labour usage of the combine-harvested arable crops. This may lead to the progressive and sequential migration of the industry away from high-wage producers towards countries that can offer the right environment and lower wage labour. This cannot occur very rapidly because the oil palm is a perennial plant that requires large investments in land, roads, planting material and mills, and new developments are both costly and time demanding. However, the way in which new planting in Indonesia is increasing its production towards and above Malaysia's level is an obvious example of this process. This change has not yet threatened Malaysia's primary position in world trade simply because Indonesia has such a large internal demand, and because political problems in Indonesia are delaying the expansion there (Section 1.4.3.1). At some stage Indonesia will reach its potential output (Mielke, 1998), but it will also meet the problems of increasing wages that now affect Malaysia.

South America has high wage rates, so that even though it has enormous areas of land to develop in the equatorial region, it may be that most of its production will always be used internally. This suggests that the next country with rapidly rising production for the international market will be Papua New Guinea, where this has already started, although wage rates there are not particularly low. The Congo (formerly Zaïre) is an obvious candidate, as it has already had very successful plantations, but it may be a long time before its political stability is so reliable that capital is prepared to move in.

1.4.2.4 Competition between products

The great advantage of palm oil is that the productivity per hectare is much larger than that for any other major oil crop (Table 1.8), thus cutting the cost of land,

infrastructure, maintenance and harvesting. Davidson (1998) neatly summarised the competitive situation of the oil palm industry by saying that the oil palm is six to seven times more labour demanding than major competitors, but it can produce anything up to ten times more oil per unit area. The competitive position therefore depends on the relative costs of labour (Tan, 1988; Gan and Ho, 1994) and of land. For this reason mechanisation is given much attention later in this book (see Sections 10.2 and 10.4.7), because mechanisation is at a much lower level than in any of the other main oil crops. The lack of mechanisation is felt particularly strongly in the harvesting operations, and there seems little hope of a major advance in the near future. This high level of productivity of land has been built up since about 1950, and the components of the agricultural system that have given this large increase are presented in Jalani (1998). Despite this, Stringfellow (2000) has queried whether the technological change that continues to sweep through most of the other oil crops has somehow missed the oil palm industry, arguing from the plateau of yield level that has persisted for nearly 20 years in Malaysia, which has the most advanced oil palm industry. In contrast, the yields per unit area of the arable oil crops have risen steadily, and are now forging ahead because of biotechnological advances, whereas biotechnology in oil palms is still at an early stage (Meunier, 1995; Corley and Stratford, 1998). If the answer to Stringfellow's query is positive, there could be a very serious danger to sections of the industry in the future. In addition to these physical factors, there are the largely unpredictable and politically motivated subsidies that support many of the other oils, and that can alter the competitive position of palm oil almost overnight. The vagaries of marketing and popular belief also affect the oil palm industry, in the arguments about the healthiness of palm oil (see Section 14.4) and the acceptability of genetically manipulated crops.

In total, the growing world demand almost certainly means that the global oil palm industry will remain successful and expanding, for as far ahead as the major world population expansion continues, which is probably until 2040–2050. However, there will be many periods of crisis induced by low prices, and the competition with other vegetable oils and between the different producers of palm oil is likely to become sharper. The palm oil industry cannot afford to be complacent during the occasional upswings in the price, and needs to have strategies ready to meet the periods of low prices (Basiron 2000; Tayeb Dolmat and Tarmizi 2001).

In particular, retail customers are becoming much more sensitive to suggestions that a particular crop is

Table 1.8 Oilseed annual yields (tonnes seeds per hectare) of the five major oilseeds competing with oil palms, on the average of the five world crop seasons 1997/98–2001/02

Average 97/98–01/02	USA	Argentina	Brazil	EU-15	World
Soyabeans	2.58	2.59	2.55	3.23	2.27
Rapeseed	1.53	1.49	1.56	3.08	1.49
Groundnuts (Shelled basis)	2.25	1.58	1.22	2.10	1.01
Cottonseed	1.13	0.61	1.52	1.63	1.04
Sunflowerseed	1.52	1.72	1.53	1.66	1.19

After Oil World Annual (2001).

damaging either to the environment or to health (Vis *et al.*, 2001) (see Section 15.3). The industry will be expected, like all others, to safeguard the land and the forests, prevent pollution of water and land, and care for biodiversity (Gurmit *et al.*, 1999a; Gurmit, 1999). The health questions have already affected palm oil for decades, and if genetically modified oil is produced, it will meet resistance in Europe at least.

Fry (2002) has assessed this problem recently using the latest data, taking into account most of the factors that Tinker (2000a) discussed in a qualitative way. In the year 2000 the sale price of the oil in Rotterdam was greater than the cost of production and transport by the following percentages: Indonesian crude palm oil (CPO) 40%; Argentinian sunflower oil 12%; Malaysian CPO 12%; Brazilian soybean oil 9%; Canadian canola oil 7%; Argentinian soybean oil 5% and USA soybean oil 1%. After taking into account estimated changes within the following 10 years, his conclusion was significantly more pessimistic than the above. This was based mainly upon the large differences in the production costs in Malaysia and in Indonesia, largely due to the higher wage rates in the former. His prediction was that by 2010, the landed cost of Malaysian CPO in Rotterdam would be greater than that of Canadian canola (rape-seed), and soybean oil from the USA, Brazil and Argentina. However, Indonesian CPO would remain as the lowest cost oil by a significant margin. The oil palm industry may prosper, but some countries will find it difficult to meet the competition from other oil crops. These need to take urgent action.

1.4.3 Single-country developments

The world oil palm industry is very complex, and it is not possible to give a detailed discussion about the state of the industry in each individual country. This section gives notes on the most important producers.

1.4.3.1 Indonesia

An area of 110,000 ha planted was achieved in 1940, but following World War II and the independence struggles, the Sumatran plantations were only slowly brought back into good condition, and further planting was very slow. By 1956 the planted area had increased by only 15% over the prewar area, and yields per hectare were low.

In the late 1960s the treecrop area in Indonesia was organised into large estate groups (PNPs) under public ownership. Seven of these held 90,000 ha in 1971 in Sumatra, and another 36,000 ha was held by private companies. During the early 1970s there were large

capital injections by the World Bank and the Asian Development Bank into the PNPs, and by 1985 the planted area was over 500,000 ha (Taniputra *et al.*, 1988). Smallholder schemes also started, and Indonesia has supported its smallholder sector strongly, including guaranteed support prices for FFB supplied by smallholders (Table 1.9). It was found possible to convert areas that had been taken over by lalang (*Imperata cylindrica*) after food cropping into productive oil palm plantations, which was a very desirable step in both environmental and economic terms. The recent distribution of the various forms of ownership of oil palms, and the distribution on Sumatra or elsewhere, is given by Lubis and Daswir (1996). The private estate sector is now the largest (Table 1.9), but the other forms are still substantial.

During and after the 1980s in particular the industry made great strides (Lubis *et al.*, 1993). From 1980 the planted area increased five-fold in 11 years, and nearly doubled again by 1996 (Fig. 1.2) (Pamin, 1998). This included moving into new areas such as Kalimantan and Sulawesi. The area of both private and smallholder plantings doubled between 1991 and 1996. In 1997 there were 165 palm oil mills working in Indonesia. Domestic consumption of palm oil increased rapidly, reaching 60% of oil production in 1997. There had always been a considerable body of research in colonial days, when the AVROS Research Institute was established in 1916, and this carried forward plant breeding very successfully: AVROS *pisiferas* are still well known in current plant production (Pamin, 1998). This has been converted into the Indonesian Oil Palm Research Institute (IOPRI), based in Medan in Sumatra.

The massive resources of land and labour in Indonesia suggest that it will become the predominant world producer in the near-medium term, so long as

Table 1.9 The development of the Indonesian oil palm area ('000 ha) during 1968–1998. In 1998 39% of the total area was immature

Year	PTP/PNP	Private	Smallholders	Total
1969	84.1	34.9	—	119.0
1975	120.9	67.9	1.3	190.1
1979	176.4	81.4	3.1	260.9
1980	199.5	88.8	6.2	294.5
1991	376.1	552.6	347.5	1,276.2
1994	411.4	796.0	585.1	1,792.5
1996	441.2	1,028.4	757.3	2,226.8
1998	489.8	1,494.5	892.0	2,876.3

After Pamin (1998) and Indonesian Oil Producer's Association. PTP/PNP estates are in public ownership.

government remains sufficiently stable and effective. Mielke (1998), on the basis of reasonably hopeful assumptions, predicted that Indonesia would become the largest producer during the 2010–2015 quinquennium, and by 2020 would be producing 44% of the world's palm oil (Fig. 1.7). However, Malaysia is likely to remain the world's largest exporter, because its domestic consumption of palm oil is so much less than that of Indonesia.

The policy background favoured foreign investment during the 1990s (Zainal Abidin, 1998; Jacquemard and Jannot, 1999b), but more recently the industry has suffered setbacks arising from the financial crisis in 1998 and the political instability that has followed it. The haste and excitement engendered by the oil palm boom occasionally resulted in poor planning. It appears that the practical needs for suitable soils and efficient palm planting were often ignored in favour of financial issues (Jacquemard and Jannot, 1999a). The outcome of this turbulent period, when the El Niño weather perturbations and forest fires have also caused much concern and low yields, cannot yet be predicted. A major consideration in the past few years has been the growing international protest at the felling of primary forest for development. The oil palm expansion has been one, though not the largest, factor in the damage done to Indonesia's forests in recent decades (Casson, 2000; Jacquemard and Jannot, 1999b) (see Section 15.3.2). It is essential that better control be exerted over the further development of forest land and wetland (Sargeant, 2001), though Guerts (2000) considered that the problems of getting land for oil palm development were comparable to the problems of raising finance. Whereas Casson (2000) expected the rate of oil palm planting to rebound soon, she noted that some companies get concessions in Kalimantan and Irian Jaya ostensibly for oil palm development, but in reality to get access to the timber reserves on it. They are therefore only interested in land carrying good forest (called 'production forest'), and will not develop degraded land. Casson (2000) formulated 13 recommendations that would prevent some of the misuse of land that is occurring. These included that the Government should ensure that concessions were really planted up, rather than just stripped of timber; should review development in certain provinces, and should direct development to degraded forest land rather than to prime 'production forest'; and should give more inducements to increase environmental concern. Hårdter *et al.* (1997) argued that when properly carried out, intensive oil palm cropping could be a sustainable method of producing food and energy in the rainforest areas of South-east Asia, and thus needs

to be encouraged. According to Poeloengan (2002), the area of 3.58 million hectare under palm plantations in 2001 produced 7.2 million tonnes. Much of this will still be immature, Table 1.9, so the yields from this will increase (see Figs 1.2, 1.3. and 1.4). The total amount of production forest allocated for oil palm plantations is 9.8 million hectare, showing the possible scale of future planting, and the difficulty of protecting prime forest.

In 1996 the Indonesian industry consisted of 2.3 million hectare of plantings, of which 50% was on private estates, 33% on smallholdings and 17% in public ownership (Table 1.9), showing a major change from the earlier preponderance of public holdings (Jacquemard and Jannot, 1999a). The increase in the smallholder and private area between 1980 and 1996 is particularly striking. The distribution of palm plantations over the widely spread parts of Indonesia is given in Fig. 1.6 (Casson, 2000). Most of these authors recognise the serious impact of the 1997/98 economic crisis, but expect the Indonesian oil palm expansion to continue, although probably at a slower rate.

1.4.3.2 Malaysia

Rehabilitation after World War II was more rapid than in Indonesia, and by 1947 the industry was already in full operation. Despite the terrorist threat at that time, expansion was rapid in the 1960s. This was often on land that had earlier carried rubber or coconuts, as the prospects of high yields and profits with oil palms were recognised, but very large areas of primary forest were also used. A total of nearly 1 million hectares of planted area was reached in 1980 (Fig. 1.2). Most of the planting in forested areas was done by federal and state agencies, including government-sponsored settlement schemes (see Section 10.8). Estate planting tended to be more on old estate land, where rubber was steadily replaced by oil palms. By this time almost all the coastal alluvium soils had been used, and progressively more inland soils and steep land were planted. In general, these soils were more marginal than those that had already been developed.

The infrastructure of the industry was greatly expanded, with the aim of adding value to the palm products exports. Local refineries were set up, and by 1980 42 refineries were processing 9000 t of oil per day (Wood and Beattie, 1981). There were then 147 plantation oil mills. This downstream movement in the industry has now gone into fractionation, and much of the Malaysian production is exported as stearin and olein (Wood and Beattie, 1981) (Section 13.5). Oleochemicals are also being developed. However, the oil extraction

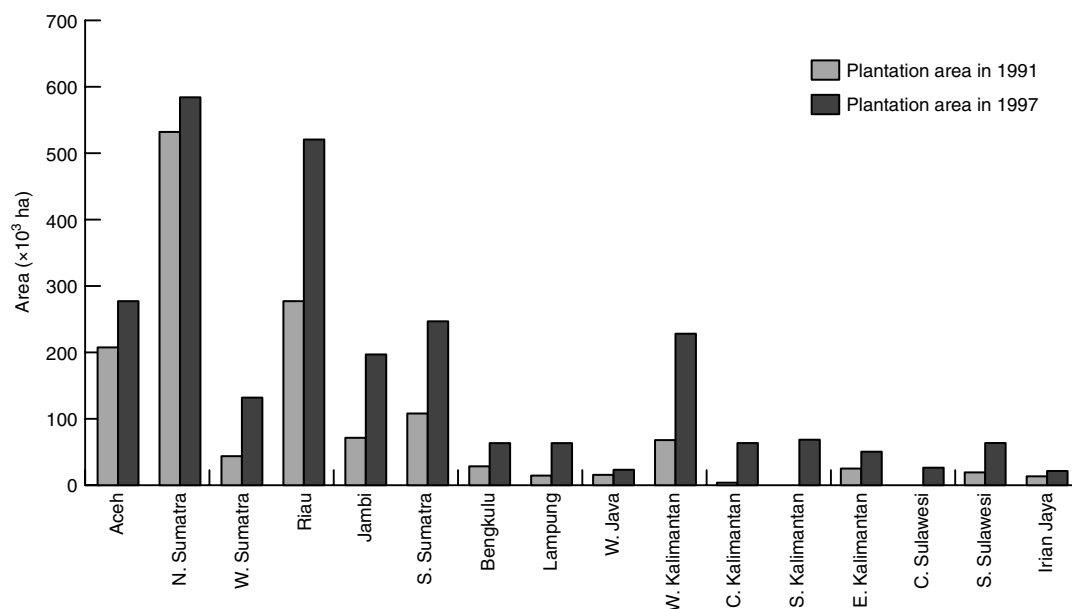


Fig. 1.6 Geographical distribution of oil palm plantations in Indonesia, and increase from 1991 to 1997. (After Casson, 2000.)

mills initially caused a major river pollution problem. The industry has developed reliable methods of effluent disposal (Ma, 1999a) and research on the environmental impact of mills continues up to the present. Another environmental problem that afflicts the industry is that some steep, forested sites have given rise to erosion, particularly where forests are first logged over before development as plantations. The increasing use of marginal land in all of Malaysia, which often means steep land, may be a cause of problems in the future especially as field mechanisation becomes more fully established (see Chapters 8 and 10).

However, the most pervasive problem is the labour shortage that has grown over the past few years, owing to the many opportunities for jobs in newly developing industry. It is difficult for the plantations to meet the wage rates now available in industry generally, and it has become dangerously dependent on using short-term immigrants from Indonesia, Bangladesh, the Philippines and elsewhere as labour. A further problem is the low oil extraction ratio that has troubled the industry since the early 1990s (see Section 10.5), which has tended to undercut what should have been a steadily growing productivity.

During the 1990s interest shifted to East Malaysia, particularly to Sabah, where the existing planted area has been greatly extended to 773,000 ha mature plantation and 168,000 ha immature plantation (Ling and Pillai,

2001). The comparison of these figures shows the speed of the expansion and Sabah now has the largest plantation area of any single Malaysian State. The soil in Sabah is fertile, and already in 1992 mean yields of 23 t/ha of FFB were being obtained on some plantations (Goh *et al.*, 1994b). The best plantings between 1971 and 1984 achieved a maximum yield of around 30 t/ha, but the period taken to reach this maximum yield decreased with time, from 12 years to 6 years in the youngest planting. The best plantings between 1985 and 1989 achieved top yields of 40 t/ha (Goh *et al.*, 1994b).

Malaysia has the most mature oil palm industry in the world, and the overall development of the country is moving very rapidly. The resulting great difficulty in finding suitable sites and suitable labour in Malaysia has led the Malaysian industry to look for expansion opportunities in other countries (Guerts, 2000). Several Malaysian companies have joint ventures in Indonesia. Kuruvilla and Mohandas (1997) outlined many of the problems of setting up a very large-scale (12,000 ha) plantation in central Kalimantan, which demanded co-ordinated action by many players. There is interest in investment in Papua New Guinea, Brazil, the Philippines, Colombia, Guyana and Honduras. Possibilities in African countries such as Burkina Faso, Congo, Nigeria and Ghana are also being considered. Guerts (2000) stated that '... the next 5–10 years should

see the supply of palm oil become more regionally diversified, even though Malaysia and Indonesia will retain their status as key players'.

At present the industry is extremely successful, and Davidson (1993) stated that the Unilever plantations had increased yields per hectare by 315% and labour productivity by 419% over the period 1951–1991. However, by far the largest improvement in productivity was obtained in the oil palm mill, rather than in the field. Tan (1988) calculated that the production costs of palm oil in 1987 were lowest for Malaysia, at US\$205/t (see Section 1.4.2.4), although this is now probably well out of date and many estates find it difficult to meet a world price of \$250/t. However, this improvement in yields seems to have slowed since about 1980, and the mean yield over the whole country is only 3.8 t oil/ha (Mohd. Jaaffar and Jalani, 1999), despite the fact that good estates produce 5–6 t/ha, and the estimated potential of recent progenies is as high as 12–13 t/ha. In a highly developed agricultural industry it is probably reasonable to expect a national mean yield of about half that of the most outstanding fields. It is not reasonable to take the top yields as those obtained by the most recently produced planting material, as the mean age of the palms will be about 10–12 years. The potential yields of the best material planted in 1980–1988 were 9–10 t (Jalani, 1998). This suggests that as a minimum, the national yield now should be 4.5 t/ha, with the estate sector reaching 6 t/ha. The potential yield gap is now the subject of much study (Tinker, 2000a; Jalani *et al.*, 2001) (Table 1.10). This suggests that there are large reserves of productivity per unit area that can be tapped in the future.

Teo (2001) queried whether Malaysia should expand its oil palm area further, and particularly whether it was justifiable to use marginal land. Indeed, if the yield gap mentioned above could be closed it should be unnecessary to open more new areas. In 1999 the Malaysian Oil Palm Board was set up, as a merger of the Palm Oil Research Institute of Malaysia and the Palm Oil Registration and Licensing Authority of Malaysia, to develop national priorities and policies for the industry, and this must surely be one of the issues to be addressed.

To reduce this yield gap the well-established current growers in Malaysia will have to move up to a new level of efficiency, as well as keeping their costs under control. It has been pointed out (Tinker, 2000a; Jalani *et al.*, 2001) that plant breeders have for many years claimed continuing increases in productive potential for their new material. Indeed, the best plantings of recent material on good sites with efficient management are capable of 9–10 t oil/ha per year. Despite this,

Table 1.10 Mean yields (t/ha) of FFB, crude palm oil and palm kernels in Malaysia

Year	FFB	Crude palm oil	Palm kernels
1975	17.95	3.66	0.74
1976	16.16	3.48	0.71
1977	16.32	3.54	0.74
1978	16.25	2.95	0.68
1979	17.76	3.65	0.79
1980	18.72	3.78	0.81
1981	19.16	3.76	0.79
1982	19.50	3.83	0.80
1983	17.45	3.43	0.72
1984	21.80	4.25	1.19
1985	22.15	4.33	1.28
1986	22.15	4.41	1.28
1987	17.10	3.39	1.01
1988	17.52	3.47	1.04
1989	19.57	3.88	1.15
1990	18.53	3.64	1.10
1991	17.85	3.48	1.01
1992	17.83	3.43	0.99
1993	20.26	3.78	1.16
1994	18.42	3.43	1.05
1995	18.93	3.51	1.06
1996	18.95	3.55	1.06
1997	19.10	3.63	1.06
1998	15.98	3.02	0.79
1999	19.26	3.58	0.91
2000	18.33	3.46	1.01
2001	19.14	3.66	1.05

After PORLA; see Tinker (2000a).

the Malaysian average production has fluctuated between 3 and 4.3 t/ha per year since the mid-1970s (Table 1.10). It is obvious from this that the industry is lagging far behind its real potential, and few other major world crops have shown such a lack of improvement in mean production per hectare at the practical level over such a long time. The yield variation and the site yield potential approaches to research (see Section 10.7.2) are therefore essential to improve agronomy and management so as to obtain these potential yields. The Malaysian industry has undoubted assets in climate, soil, plant material, and skilled labour and management, and has every chance of closing this yield gap. Chan *et al.* (1999) have reviewed the challenges that the Malaysian industry is facing.

1.4.3.3 Other Asian countries

The most important new oil palm producers are Papua New Guinea and Thailand. Both are close to the present focus of the world oil palm industry in Malaysia and

Indonesia, so that the soils and availability of advice and capital are supportive.

The palm oil industry in Thailand is growing rapidly, with a planted area up from 110,000 ha in 1988 to 320,000 ha in 1999. All of the latter area is expected to be harvested by 2001. The latest output figure for Thailand is 429,000 t. However, so far the production of palm oil is only slightly more than the demand, and Thailand is a small exporter of palm oil (Table 1.4), as was predicted for 2001 by Sarakoon (1998). Most of the production is from smallholder or co-operative plantings, and the climate is less advantageous than that of Peninsular Malaysia, so yield per hectare is still low and costs are high (Sarakoon, 1998). Irrigated plantings are now being tested (Palat *et al.*, 2000).

Papua New Guinea is now a significant producer, with an output of 277,000 t in 1999/2000, and exports of 294,000 tonnes of oil in 2000 (Table 1.4). The climate and soils are very suitable, although the rainfall is excessive in some areas, with around 5000 mm rain/year. This country also has a smallholders' development scheme (see Section 10.8.1.2), which has been highly effective. There is developing interest in growing palms in India, probably encouraged by the very large imports in recent years. The climate is not favourable and yields are still quite low (Rethinam, 1998).

1.4.3.4 Nigeria

Nigeria lost her position as the largest producer of palm oil to the Congo in 1962, regaining it temporarily in 1964/65 because of the problems in the Congo. After that it fell further and further behind the Far East producers, so that now its palm oil output is stated to be only about one-tenth of the Malaysian output, although the Nigerian production may well be underrecorded to some extent (Table 1.2). The latest statement from within Nigeria (Omoti, 2001) is that Nigerian production of palm oil is 960,000 t, all of which is consumed within the country, which also imports palm oil, as the demand is over 1 million tonnes (Omereji, 1995). The kernel production is around 400,000 t, which suggests that oil/bunch is less than two and a half times as large as kernel/bunch. The causes of this change are four. First, the Nigerian population grew rapidly, and its demand for palm oil grew even more. Secondly, the price offered to the farmer for palm oil by the marketing boards was for long periods very low, sometimes little more than half the export price (Ataga, 1986; Hartley, 1988). This was equivalent to a heavy tax on the farmers, which discouraged both harvesting and planting, and it was a great step forward when the Nigerian Palm

Produce Board was abolished in 1986. Thirdly, Nigeria fell woefully behind the Asian producers in developing modern plantations, thus continuing for far too long with attitudes that had begun in the 1930s (Section 1.3.1). Even now the total planted area is only 245,000 ha, including all smallholders (Table 1.2) (Omoti, 2001). Finally, civil strife and government mismanagement were serious impediments to the industry. As a result of this, most of the research work produced at the West African Institute for Oil Palm Research in Nigeria was wasted for West Africa, even though it was often found to be valuable in the Asian industry.

However, before this period of decline there was considerable improvement in the quality of the oil produced, in terms of free fatty acid (FFA) content. This had always been very high, and some ethnic groups in West Africa actually prefer this. However, by offering a sharp price differential almost all Nigerian oil reached a grade of 4.5% FFA and subsequently 3.5% by 1963. It seems likely that the Nigerian industry, however it develops, will remain solely a supplier to the internal market. Nearly 100,000 t of oil were imported to meet internal demand in 1999, so import substitution is attractive.

Many development schemes, some with external funding by international bodies, have been launched for state-owned plantations and for smallholder developments over the past few decades, but it is clear that very few of these met their targets (Ejemba, 1989). However, some 66,000 ha of palms in total were planted by these schemes. It has been difficult for private estates to be set up, because the complex land tenure systems alone are a great barrier, and the low returns and difficulties of management have been discouraging. However, the state schemes began to be privatised after the 1986 reforms, and several states are now making serious efforts to make improved planting material available to their farmers; some 4 million seeds were planned for delivery in 2001. Omereji (1995) recommended that the main emphasis in expansion should be placed on the smallholder sector, because of the poor results of the estate developments in the past.

There is still considerable interest in the wild grove palms, which cover a total of 2.1 million hectare, and they contribute by far the largest part of the total yield (Table 1.12) (Omoti, 2001). A scheme was introduced by Anambra State to encourage farmers to replace grove palms with improved *teneras*, and around 3000 ha may have been improved in this way. The Nigerian Institute for Oil Palm Research (NIFOR) is now distributing improved seed, and since 1985 has distributed nearly 35 million seeds.

It seems clear that traditional methods of extraction (see Section 13.4.2) are still being used to a significant extent (Ilechie and Omoti, 2001), but there is great interest in producing small semi-mechanised systems of extraction. NIFOR has developed a small plant (Small Scale Processing Equipment) in various sizes that meets the requirements of small estates, smallholders and farmers of wild palm, and can be constructed of largely local components (see Section 13.4.4).

1.4.3.5 Democratic Republic of the Congo

By 1959 the Congo had made great advances, with 147,000 ha in industrial plantations and nearly 100,000 ha planted by local farmers. Production in 1959 was 240,000 t, of which three-quarters was exported (Hartley, 1988). The best yields were 3 t oil/ha, which was outstandingly good for Africa, and good even for the Malaysian industry at that time. This high standard was in large measure a result of the excellent work of the Institut National pour l'Étude Agronomique du Congo Belge, whose activity was greatly lessened in later years. As in Nigeria, the increasing local population consumed a steadily greater amount of the oil produced, and political unrest and failure diminished production, so that output of oil is now barely 100,000 t/year and there appear to be no exports (Oil World, 2000).

1.4.3.6 The Ivory Coast

This country has benefited from the work of the French organisation Institut de Recherches pour les Huiles et Oléagineux (IRHO), now reorganised and renamed into Centre de Co-operation Internationale en Recherche Agronomique pour le Développement (CIRAD). The country has a moderately suitable climate, but with the west African dry season. The development of modern plantations started in the 1960s (Anon., 1983), and was operated by the Société d'État pour le Développement du Palmier à Huile (Sodepalm) and by Palmindustrie, in a mode that involved local people as both owners and workers; both organisations have now been privatised. These plans were successful (Hartley, 1988), and by 1981 there were 52,000 ha of industrial plantations and 33,000 ha of associated plantings by smallholders. The output has steadily risen, but as in other African countries local consumption has increased more rapidly. Exports thus peaked at 114,000 t in 1975, and by 1999 had fallen to 100,000 out of a total production of 288,000 t, both figures being variable but with no clear trend over the past few years.

1.4.3.7 Other West African countries

Differing amounts of palm oil and kernels are produced in several other West African countries. Of these, Cameroon has had considerable industrial planting by the Cameroons Development Corporation (CDC) and by Unilever (Courade, 1978) in West Cameroon, and by Société Camerounaise de Palmeraies (SOCAPALM) in East Cameroon. Apart from direct planting, an out-growers' scheme was started by SOCAPALM (van der Belt, 1981). Current production is about 145,000 t, with exports of 14,000 t; about 61,000 t of palm kernels were produced, with virtually no exports of kernels or kernel oil. Production is thus well balanced with internal demand at present, and it is to be expected that the internal demand will increase progressively. The rainfall gradient across Cameroon is not as sharp as in the more westerly African states, and the climate is good for oil palms in many areas.

Benin has a very marginal climate for oil palms, with a well-defined and intense dry season and relatively low rainfall. Interest in oil palms first arose because of the extensive palm groves in the south of the country, on degraded agricultural land (Hartley, 1988). The yield levels were very low, and despite attempts to build up a plantation industry, the oil output is very small and exports are nil. Some 22,000 t of kernels is still produced.

Other countries producing small amounts of palm products, but requiring imports to satisfy their needs, are Ghana, Sierra Leone and Liberia; Ghana has small exports, but they are less than the imports.

1.4.3.8 Brazil

South and Central America is considered to be a prime area for oil palm expansion (Anon., 1999). However, several diseases that are not encountered elsewhere in the world can be very serious in the Americas (Gomez *et al.*, 1996) (see Chapter 12), and this has undoubtedly held back development of large plantations on the Asian model.

Brazil has probably the largest potential area that could be used for oil palms, as the whole of the Amazon basin has an equatorial climate, and was or is covered by rain forest (Ooi *et al.*, 1982). Sanz Veiga (1998) estimated that some 70 million hectare was suitable for oil palm cultivation. There has been some discussion about whether very extensive clearance of the Amazon forest, as is occurring to some extent now, could lead to a substantial change in the local climate (Tinker *et al.*, 1996). There is some evidence, largely theoretical, that

a change to grassland or other low-growing crops might cause such a change, because it alters the energy relationships and hence the evapotranspiration. The consequences of clearance followed by establishment of oil palm plantations is not known, but it is probably one of the safest ways of developing this large area. General considerations suggest that the climatic results with mature palms would be much more like those with high forest than with grassland. However, Brazil is still only producing about 95,000 t of oil, although plans for increasing production have been made over a number of years (Nascimento *et al.*, 1982).

1.4.3.9 Colombia

Colombia is the largest producer in South America, with a plantation area of 148,000 ha in 1997. The plantations are widely spread over its regions, though mainly in the Llanos Orientales in the eastern part of the country, in the Magdalena valley and on the Pacific coast (Guerra de la Espriella, 1984). The industry has been set back by continuing serious internal unrest. There are around 2000 producers, although 50% of these have less than 5 ha planted, but in 1999 the national mean yield was at the very respectable level of 3.9 t/ha. Corley (1992) considered that yield potentials were promising. Current production is 510,000 t of oil, and 100,000 t of kernels. Recent increases have produced an exportable surplus of around 100,000 t of oil, and Colombia has published a plan for oil palm development that envisages expansion to 740,000 ha by 2020 (Fedepalma, 2000), which would make Colombia a major exporter of palm products (Mesa Dishington, 1998). A recent review (Anon., 1999) emphasized the future importances of Latin America as a palm oil producer, and singled out Colombia, Ecuador and Central America as especially promising.

1.4.3.10 Costa Rica

Development has been moderately rapid; 30,000 ha of medium- to high-technology plantations existed in 1996 (Umaña, 1998) and output was around 113,000 t, of which 62,000 t was exported (Duran *et al.*, 1999). The areas of oil palm production are mainly on the alluvial plains on the Pacific coast, where the soils are fertile and suitable for the oil palm, in the Quepos and Coto regions (Esperalta, pers. comm.). Conditions are suitable, but the rainfall is very high. There is a research organisation with a good research programme, especially in breeding, and the mean yield of oil was 4.0 t/ha in 1996 (Umaña, 1998a, b).

1.4.3.11 Ecuador

Planting in this country started on the Pacific plain, but later planting went ahead more rapidly in the Oriente region, east of the Andes and therefore part of the Amazon plain. A research station was established there in the 1960s. Production is now about 240,000 t/year from about 125,000 ha and rising quite rapidly (Loaiza Granda, 1998). The size of the estates varies widely.

1.4.3.12 Other South and Central American countries

The planted oil palm was originally introduced to Honduras in 1927, but did not develop widely until the 1950s and 1960s. Honduras is now a large grower, with about 50,000 ha in 1996. Several other countries have land with the necessary climate in South and Central America, and nearly all these have varying numbers of oil palms. Venezuela had 22,000 ha of palms planted by 1996, which was used within the country, meeting 13% of total needs for fats and oils (Carrero, 1998). Peru has large territories in the Amazon plain, but output remains fairly small. Mexico (Velázquez-Cágal *et al.*, 2001) has about 3000 ha of oil palms, despite its northerly situation, and plans to expand these to 50,000 ha (Núñez Virrueta, 1998).

1.5 DEVELOPMENT METHODS

1.5.1 Main mechanisms of oil palm development

The first distinction lies between wild or semi-wild and planted palms. The existence of the palm groves of west and central Africa provided the raw material of a major world industry, with little prior investment. It allowed the markets and applications for use of palm products to be tested and developed, and the appearance of growing markets for palm oil during the nineteenth century led the development of the modern plantation industry. As soon as these uses had become established, demand grew automatically with the wealth of the developed countries, and it became logical to cultivate the oil palm. However, as has happened many times in the past, once cultivation and domestication have become fully established, there is no economic place for the wholly or half-wild plant or animal. The decline of the groves was therefore entirely predictable, and this decline was a measure of the growing maturity of the industry. The biodiversity of the various types of dense or thinned grove described in Section 1.2.3 will

Table 1.11 Land development targets and achievements in Malaysia, by agency, 1971–1990

Programme	2nd Plan (1971–1975)		3rd Plan (1976–1980)		4th Plan (1981–1985)		5th Plan (1986–1990)
	Target	Achievement	Target	Achievement	Target	Achievement	Target
FELDA	121,408	161,900	202,347	206,819	161,600	161,600	175,500
FELCRA	40,470	23,576	20,235	27,134	41,100	31,100	–
RISDA	60,705	19,122	40,470	12,341	9,770	9,770	–
State	136,504	143,667	97,127	146,466	217,200	158,000	93,700
Joint venture/ private sector	90,045	55,502	44,516	64,545	100,000	57,100	17,500
Total	449,132	403,767	404,695	457,305	529,670	417,570	286,700

After Shamsul Bahrin and Lee (1988).

always be low compared with natural forest, so the arguments for retaining them on sustainability grounds are somewhat weak. There have been several prospecting programmes in the groves of West and East Africa and America, the latest being by the Malaysian Palm Oil Board (MPOB) from Malaysia, and the biodiversity of the oil palm has probably been sufficiently captured.

1.5.2 Plantations

The major distinction in development was between planting of palms by large companies with ample capital working at the 1000 ha level or above, and farmers' plots of a few hectares, farmed alone or in small co-operative groups. Apart from their better planting material, plantations have always had advantages over farmers' plots in the production of large amounts of commodity materials, because they are based on tight, managerial control of routine tasks carried out efficiently (Webster, 1983). There may be an advantage for those smallholder crops that require careful and detailed attention, such as rubber or cocoa, where smallholders may be able to achieve higher yields because of their personal attention. However, there is nothing of this nature in the oil palm, where maintenance and harvesting activities are usually physically demanding, but basically fairly simple procedures. Regular fertilising, maintenance and above all harvesting are essential to produce high yields and high quality, and this is most easily obtained under the plantation systems. In addition, there is the essential need for a mill to extract the oil and kernels from the bunches, and a plantation and mill can be designed to fit each other's requirements.

A tendency to lean towards either estates or smallholders seems to have been avoided in South and Central America, and instead there have been more privately

owned medium-sized holdings with small locally designed mills. These small estates have become progressively more successful, which seems to contradict the widely held view that oil palm plantations give great economies of scale. The oil produced is largely sold locally, so that uniform quality is less important, which is fortunate, as the local mills vary greatly in efficiency (Hartley, 1988).

1.5.3 Smallholders

Although many farmers maintain their plots well, the average standard will almost always be below that of plantations, giving lower yield and quality. Irregular harvesting or delayed transport of fruit to the mill by a significant fraction of farmers will produce bulked oil of substandard quality. The main problems in smallholder schemes are oil quality, field discipline and reliability of FFB supplies to the mill.

Nevertheless, there has always been pressure for oil palm cultivation by smallholders, partly from the would-be farmers seeking a better life, partly from politicians who see this as a desirable way of finding work for unemployed young men and building stable rural communities. This driving force is shown by a quotation from a Malaysian government working party in 1955: 'there is a very real need for planned and co-ordinated development of land so as to ensure that economic development goes hand in hand with social development' (Shamsul Bahrin and Lee, 1988). From this sprang the Federal Land Development Authority (FELDA), which is a good example of successful land settlement and development schemes. The total areas of land developed in Malaysia by the state and private sectors are shown in Table 1.11. The schemes vary but FELDA preferred a minimum size of 1800 ha for 400 families, i.e. about 4 ha per family, plus residential and

Table 1.12 Projected and actual number of settlers in Malaysia, by Plans, 1961–1990

	Projected	Actual	%
2nd Malaya Plan (1961–1965)	24,000	6,083	25.3
1st Malaysia Plan (1966–1970)	12,745	11,863	93
2nd Malaysia Plan (1971–1975)	20,000	13,779	69
3rd Malaysia Plan (1976–1980)	25,500	29,566	115
4th Malaysia Plan (1981–1985)	30,000	30,284	101
5th Malaysia Plan (1986–1990)	30,000		

After Shamsul Bahrin and Lee (1998).

infrastructure areas. The maximum size was around 2600 ha for 600 families: above this the commuting distance became too large, and if families were dispersed, it became difficult to provide essential services such as schools. The intake of settlers into the FELDA schemes (Table 1.12) increased with time, and the percentage of the planned numbers attained has been around 100% since 1976. FELDA schemes are larger now, as increasing wealth allows the purchase of motorcycles, giving workers greater mobility. With oil palms, a central oil mill is also essential, so a reasonable area is 4000 ha. The basic facts that make a reasonably sized oil palm plantation efficient also make themselves felt in smallholder schemes, and thinking within FELDA appears to be in favour of still larger contiguous blocks of land for oil palms.

This system allowed land of suitable soil types to be reserved for settlement, rather than allocated randomly (Shamsul Bahrin and Lee, 1988, p. 40). The land was held in co-operative ownership (Shamsul Bahrin and Lee, 1988, p. 53), so that all had a stake in the land, but individual parcels were not distributed until the settlers had shown their competence in cultivation. Later settlers were given title to their individual plots, and this system caused a feeling of ownership and responsibility in the settlers. Later, FELDA adopted a share ownership system, in which settlers received wages for their work, shares in the whole enterprise equivalent to 4 ha and dividends on this. Ultimately, settlers are given their share certificates and titles to their house plot. The management of such settler schemes is now the subject of international negotiation (Fold, 2000).

From about 1980 onwards FELDA extended its operations to Sabah. By 1985 FELDA schemes were producing 986,800 t of oil. Its share of area planted in Malaysia was 32%, and of oil produced was 25%, a successful outcome for a series of settler schemes.

Indonesia has also had extremely rapid expansion of smallholder schemes on somewhat similar lines to the

above (Table 1.9). In the Lower Ague project of Honduras there is also a co-operative approach, with about 100 settlers working some 300 ha. In the Ivory Coast the approach has been to set up nucleus estates, with mills capable of taking greater inputs than expected from the estate alone. Smallholdings are grouped around this mill. However, it has been found in practice that the estate has to be relatively larger than would be expected in a smallholder scheme (Hartley, 1988), because of the risk that smallholders would not supply bunches to the mill consistently. In New Britain (Papua New Guinea) a similar scheme has been very successful, with ratios of estate to smallholder land at 2:2, 3:4 or 1:2. In Benin co-operatives for smallholders were set up (Adje and Adjadi, 2001), whereas in Cameroon only estates were developed. Nigeria has a smallholder sector that appears to be stronger than the estate sector (Omereji, 1995), but this is not reliant upon large estate mills. In the Philippines there is an out-grower scheme grouped around nucleus estates, with about one-quarter of the area managed by smallholders.

1.5.4 Research

Simple research and development has been important since the first plantations were established. Taking a wild and naturally reproduced plant into mass planting raises many questions of planting, seed treatment and so on, and these must have been dealt with by the early pioneers, probably with help from Botanical Gardens and Agricultural Services in Indonesia and Malaysia. However, a need was felt for a dedicated research facility, at least partly because research in temperate zone agriculture was developing rapidly. The first was a research station of Algemeene Vereniging van Rubber Planters ter Oostkust van Sumatra (AVROS) at Medan in Sumatra [now the Indonesian Oil Palm Research Institute (IOPRI)] in 1916. As the name shows, the initial interest was in rubber, but oil palms began to be investigated quite soon, and a very positive report on this was made in 1922 (Pamin, 1998). This was, by a large margin, the first organised professional research on oil palm cultivation. Secondly, in the 1930s work started in the then Belgian Congo at Yangambi, at Institut Nationale d' Étude Agriculture du Congo (INEAC), and led to the discovery of the relationship of *tenera*, *dura* and *pisifera* palms. Thirdly, the West African Institute for Oil Palm Research was set up in Benin City, Nigeria, shortly after World War II. Later research facilities were set up in the Ivory Coast at La Mé, and in Dahomey (Benin). In Malaysia research was for a number of years largely pursued by the individual

private companies, and their contribution proved to be vital (Chew *et al.*, 1998). Subsequently, the public Malaysian research programme was set up as the Palm Oil Research Institute of Malaysia (PORIM), now the Malaysian Palm Oil Board. Gradually, all countries that are seriously involved with oil palm culture have set up research organisations of some form. Chew (2001) noted the importance of research and development for estate management of oil palms, to improve efficiency and lessen costs.

Research has produced many valuable advances for the industry in the past. It will be even more important in the future, because of the intensely competitive nature of the international agricultural industry and the rapid strides being made in research into other crops. The advantages of annual crops over perennial crops in a research race have been outlined by Tinker (2000a), and the oil palm industry will have to ensure that its research strategy is correct if it is to hold its present strong position.

Chew (2001) recently discussed the needs for research in Malaysia, in both the public and the estate sector. He considered that more effort should be put into determining the most useful research programmes, and that these needed a proper balance of basic, strategic and applied research. Currently, the basic research on biotechnology and related subjects receives much attention, work on clonal palms and plant breeding is well supported, and simple applied work is done because of pressing needs to solve specific problems on estates. However, more strategic work on agronomy is needed in view of the yield gap, and Chew (2001) suggested that the most important issues now were to obtain more data sets and proper analyses of estate yields and costs, climate and soils resources, and best agronomic practices. These could establish benchmarks for palm and labour productivity.

A particular feature of the past two decades has been the rise in environmental consciousness in the oil palm industry (Gurmit, 1999; Chan, 2000b) and several research programmes have been started (Gurmit *et al.*, 1999a). These have included various methods of integrated pest management such as the use of owls to control rats (Chapter 12). A successful research programme has been the prevention of pollution from oil mills, particularly river pollution. The most emotive issue has been the loss of old high forest (Casson, 2000) and of wet-lands (Sargeant, 2001) to planting with oil palms. Both ecosystems have very high biodiversity and are particularly sensitive. It is difficult to see how research can overcome this problem fully, because forest on land for development will be felled. Some may be used for oil palms, and the biodiversity cannot be re-created on

the original palm plantations. However, it may be possible to use whole landscapes in more ingenious mixtures of forest and plantation that will maintain the wild populations over the whole area (Szaro and Johnstone, 1996; Vis *et al.*, 2001). The use of forest land for oil palm may now be exaggerated because Hårdter *et al.* (1997) stated that 90% of cleared forest land is used for agriculture.

1.6 TRADE IN AND USE OF OIL PALM PRODUCTS

1.6.1 Trade in oil palm products

The European Union (EU) has traditionally been the main importer of palm oil; originally the UK was the largest market, but since the decline of Nigerian exports the Netherlands and Germany have become more important. Nevertheless, the EU was still the largest importer of palm products until quite recently.

There have been three periods in which countries outside Europe have imported palm products on a large scale, one of which is still continuing. First, the USA imported up to 20% of the world supply of palm oil in the years before World War I. After the war a large import continued until 1937, when it peaked at 183,000 t. After this it declined sharply to 30,000 t. The US imports have increased again very recently, but the 1999 import of 160,000 t of palm oil is very small relative to the total US usage of oils and fats, and the total world supply of palm oil. There are well-known reasons for this relatively low import, which are discussed in Chapter 14.

Secondly, the USA bought large amounts of palm kernels, up to 90% of world supply in 1937. A smaller but still substantial import continued into the 1960s. This was ascribed by Hartley (1988) to the United States Public Law 480 and other aid programmes, which for a period made it cheaper for US manufacturers to buy vegetable oils from foreign than from US sources. The USA is the largest producer of vegetable oils in the world, mainly soya bean oil.

However, the most striking change in trade has been the growth since the 1970s in importation of palm oil into countries with large and increasingly wealthy populations, such as Egypt (500,000 t), China (1,420,000 t), India (3,380,000 t) and Pakistan (1,095,000 t). Astonishingly, India's imports were less than 700,000 t only 5 years ago, but its consumption is now slightly greater than that of Indonesia (2,965,000 t). Otherwise, most countries use palm oil to a significant extent to make up the total world consumption of nearly 21,000,000 t. This gives a well-spread market for oil products, but there may be an uncomfortable dependence upon large countries

such as China that may change their purchasing policy in a relatively short space of time. The major weakness is the failure to penetrate the US market to any major extent, despite its large purchases in the 1920s and 1930s (Sections 1.6.4 and 14.4.2).

The main importer of both kernels and kernel oil is still the EU, but the import of the rest is taken by a long list of other nations. The only substantial buyer of kernel oil is the USA. A large fraction of the kernel production is now crushed in the country of origin, so that total world trade in kernels has become less than one-third that of kernel oil.

1.6.2 Traditional uses of oil palm products

The interchangeability of oils has steadily increased with lipid technology, and the oil used often depends on the current price and availability. Previously, the main uses of palm oil were in soap, margarine and cooking fat. There have always been both food product uses and technical uses, but the latter have changed progressively (Schwitzer, 1980). The lower quality oil is used for non-edible purposes, such as soaps, resins, candles, glycerol, fatty acids, inks, polishing liquids and cosmetics.

Palm oil is now used largely for food products, because of the great increase in its quality and availability in the past half century. It has also become a more diverse material, as refining, fractionation and hydrogenation (Sections 1.6.4 and 14.3.3) have become more widely used, often in the producing countries. Malaysia has been at the forefront of this, so that it now produces seven different basic products: crude palm oil (CPO), neutralised palm oil (NPO), refined bleached and deodorised palm oil (RBD), palm olein, palm stearin, palm kernel oil and palm kernel cake or meal (Wood and Beattie, 1981). Palm oil is well suited to many food uses, particularly cooking fats and deep-frying oil, and it appears in bakery products, potato crisps and other snacks, and ice-creams (Wood and Beattie, 1981). The stearin high melting point fraction is used for shortenings, vanaspati and bakery fats, whereas olein, which has a lower melting point, is used for cooking oils, margarine and salad oils. Some of these uses are relatively recent, such as fatty acid manufacture, oleochemicals in general, additives to animal feed stuffs, potato crisp making, and pastry, biscuit and ice-cream making, confectionery, bread and cakes (Section 14.3.4). Genetically manipulated palm oil (Parveez *et al.*, 1999) with an increased oleic acid content may become available in time, and will make palm oil still more flexible for use in foodstuffs, and more competitive with other edible oils, but does not seem likely to change its uses fundamentally.

A new aspect of food crop production is the recent popularity of 'organic foods', which has some links to the general concept of sustainability. The organic movement is now almost world-wide, and is taking up to several per cent of the total food market in some developed countries. The essence is to produce crops in such ways that no artificial compounds (fertilisers or pesticides) are used, and many other rules aimed at maintaining a healthy soil have to be followed. Most scientific assessments of food from organic crops conclude that there is no advantage over conventional methods used by developed agriculture (Tinker, 2000b, 2001). Nevertheless, if there is a demand for organic food the market will provide it, especially as organic food usually commands a price premium of around 50% over the conventional product. It appears somewhat unlikely that plantation oil palms will be grown according to organic rules, because of the problems of handling and transporting separate grades of oil, and of agreeing what constitutes an organic oil palm (Nampoothiri, 2001). However, organic palm oil is now on offer from Brazil.

1.6.3 New uses of palm oil

1.6.3.1 As oleochemicals

Many new compounds are now produced from palm oil and are known collectively as oleochemicals. Most of these are molecules with different fatty acid chains attached to various simple functional groups, such as acids, amines or alcohols (Basiron and Salmiah, 1994; Pamin, 1998; Miyawaki, 1998), and include sulfonated methyl esters, polyols and polyurethanes. In 1995 the estimated output was around 800,000 t in Malaysia, out of less than 10 million tonnes of oil. The world production was over 5 million tonnes, produced from a range of oils. In addition, several minor constituents of palm oil can be extracted and used separately, such as carotene, vitamin E and sterols.

1.6.3.2 As biomass and internal combustion fuels

Biomass means any organic plant product that has general uses. Palms produce up to 40 t/ha of dry matter per year, of which less than 10 t is used for extraction of oil and kernels. The rest can in theory be used for paper, filling in building boards and many other purposes, even as a general solid fuel (see Section 13.6.1) (Basiron and Salmiah, 1994; Jalani *et al.*, 1999). The removal of all this dry matter may change the palm ecosystem and the soil composition, but at present this does not

appear to be a serious difficulty. This is becoming a new product from the palm plantations, but it is not yet on a large scale.

MPOB has been working for a number of years on making a substitute for diesel fuel from palm oil. This works well enough in practice, but its acceptability depends on the relative prices of petroleum oil and palm oil (see Section 14.3.6.2). Palm diesel is made by forming the methyl ester of the fatty acids in palm oil (see Section 14.3.6.2). Its properties make it analogous to diesel fuel, and cars and buses have been successfully operated with it. However, it tends to be more expensive than diesel, unless fuel taxes are altered to favour it strongly. Fluctuations in the price of petroleum make it difficult to predict the future for palm diesel.

‘tropical oils’ in the USA. A campaign was launched by the soya bean interests in the USA (Berger, 1981; Enig, 1998) to lessen competition from palm oil and coconut oil. The latter product has decreased in international commerce, so that palm oil has in practice been the main target. There is no doubt that the campaign has had considerable success, as shown by the small imports of palm oil into the USA for many years (only 161,000 tonnes in 1999/2000). The basis for this campaign was the claim that unsaturated fats and (mainly) oils were much more healthy than saturated fats, as the latter were considered to contribute to heart ailments by leading to a higher blood content of cholesterol (see Section 14.4).

1.6.4 The conflict over ‘tropical oils’

The past two decades have been marked by a strong publicity conflict over the use of what have been called

Chapter 2

The Classification and Morphology of the Oil Palm

2.1 CLASSIFICATION OF OIL PALMS

The family of palms, the Arecaceae (formerly known as the Palmae), has always formed a distinct group of plants among the monocotyledons. The Arecaceae are placed in the order Arecales (Cronquist, 1981), although Bentham and Hooker's *Genera plantarum* placed the palms with the Flagellariaceae and Juncaceae under the series Calycinae, while Engler and Prantl's system placed them separately under the order Principes. The oil palm, *Elaeis guineensis* Jacq., is grouped with *Cocos* (the coconut) and other genera in the subfamily Coccoideae.

The genus *Elaeis* was based on palms introduced into Martinique, the oil palm receiving its botanical name from Jacquin (1763). *Elaeis* is derived from the Greek word *elaion*, meaning oil, while the specific name *guineensis* shows that Jacquin attributed its origin to the Guinea coast. There are currently three accepted species of *Elaeis*. The first two, *E. guineensis* and *E. oleifera*, are the African and American oil palms described in this chapter. The third species was previously known as *Barcella odora*, but was named *Elaeis odora* by Wessels-Boer (1965); it is not cultivated, and little is known about it. Henderson (1986b) illustrated the bisexual inflorescences, and considered that the species was quite distinct from *Elaeis*. However, molecular markers (see Section 5.2.8) indicated that inclusion of *E. odora* within the genus *Elaeis* is justified (Barcelos *et al.*, 1999): the genetic distance between *E. odora* and the other two species of *Elaeis* was similar to the distance between the latter, and less than the distance from *Cocos nucifera*, another member of the Coccoideae subfamily.

From time to time other specific names have been attached to supposed species of *Elaeis*, but none has shown any signs of permanency other than *E. melanococca*, now named *E. oleifera*, and *E. madagascariensis*. *Elaeis madagascariensis* Becc. was described by Beccari (1914b) as a separate species on the basis of material sent to him by Professor Jumelle. This material was distinguished from *E. guineensis* on some

flower and fruit characteristics, but in view of the wide variation in many minor characters in the oil palm it is doubtful whether these differences justify the naming of a separate species. Based on observations in the field in Madagascar, Rajanaidu (1987) considered that specific status was not justified.

2.2 THE AFRICAN OIL PALM, *Elaeis guineensis* JACQ.

Elaeis guineensis is a large, pinnate-leaved palm having a solitary columnar stem with short internodes (Plate 1A). There are short spines on the leaf petiole and within the fruit bunch. The separate upper and lower ranks of leaflets on the rachis give the palm a characteristic untidy appearance. The palm is normally monoecious with male or female, but sometimes mixed, inflorescences developing in the axils of the leaves. The fruits are borne on a large, compact bunch. The fruit pulp, which provides palm oil, surrounds a nut, the shell of which encloses the palm kernel.

The early descriptions of the oil palm are listed in Hartley (1988, p. 48). The only one of more than historical interest is the botanical description by Jacquin (1763). He described the palm from material from Martinique (to where it must have been introduced); his description was detailed, but he described the flowers as either female or *hermaphroditi steriles* and seemed unaware that flowers of the two sexes were in separate inflorescences. The production of male and female inflorescences was first recorded by Miller in his *Gardener's dictionary* (London, 1768). Before the end of the eighteenth century Gaertner (*De fructibus et seminibus plantarum*, Stuttgart, 1788) gave a more detailed description of the flower parts, recording that the male and female flowers are on separate inflorescences.

Most of the early attempts at classification of varieties were unsatisfactory, as they were based on very limited acquaintance with the palm, and no knowledge of the inheritance of the characters described. Of interest,

however, is the first description by Preuss (1902) of the *lisombe* palm, a name used in Congo, Cameroon and Nigeria for the thin-shelled *tenera* fruit form and still employed in quite recent times. Janssens (1927) and Smith (1935) provided the first simple classifications which, in their essentials, have stood the test of time (see Table 2.1 and Section 2.2.2.6). Although nothing was known of the inheritance of the characters described, Janssens recognised that the fruit forms *dura* and *tenera*, distinguished by the thickness of shell, could be found in fruit types of different external appearance. Thus, both the common fruit type *nigrescens* and the green-fruited *virescens* were divided by Janssens into three forms, *dura*, *tenera* and *pisifera*. The white-fruited *albescens* was also recognised, but only a *dura albescens* had been found. Similarly, although *dura* and *tenera* forms of the mantled fruited *Poissoni* were found, no green-fruited mantled specimens were discovered. Smith, however, recognised both mantled and unmantled *nigrescens* and *virescens* fruit, called them 'types', and divided all four into thick-shelled and thin-shelled 'forms'. In the Far East Schmölle (1930) used the term fruit form as early as 1929. This was described as the most complete and logical of the empirical classifications by Beirnaert and Vanderweyen (1941a), and established the use, in English publications, of the fruit-type and fruit-form classification. The term variety is inappropriate for the *tenera* and other forms, either in the botanical or in the plant breeding sense, as material will be heterogeneous for most characters other than shell thickness. Some

authors still persist in using the term variety, however (e.g. Shah and Lim, 1996).

2.2.1 Morphology and growth

2.2.1.1 The seed

The oil palm seed is the nut which remains after the soft oily mesocarp has been removed from the fruit. It consists of a shell, or endocarp, and one, two or three kernels. In the majority of cases the seed contains only one kernel, since two of the three ovules in the tricarpellate ovary usually abort. Abnormal ovaries sometimes occur and four- or five-seeded nuts may, very rarely, arise from these. In botanical terms the kernel is the seed, but in common parlance the word 'seed' is used for the nut, comprising shell and kernel, since it is the nut that is stored, germinated and planted (Fig. 2.1).

Nut size varies greatly and depends on both the thickness of the shell and the size of the kernel. Typical African *dura* nuts may be 2–3 cm in length and average 4 g in weight, although some are larger. Deli *dura* nuts average 5–6 g and range up to 13 g. African *tenera* nuts are usually 2 cm or less in length and average 2 g, but very small nuts weighing 1 g are not uncommon (Plate IID).

The shell has fibres passing longitudinally through it and adhering to it, and drawn into a tuft at the base. There are three germ pores corresponding to the three parts of the tricarpellate ovary, but the number of functional pores corresponds to the number of kernels

Table 2.1 Fruit forms and types

Character	Terminology	Description
Fruit types		
External colour	<i>Nigrescens</i>	Anthocyanin in exocarp, black or brown apex to fruit
	<i>Rubro-nigrescens</i>	Apex brown, rarely covering more than half of the fruit; base orange
	<i>Rutilo-nigrescens</i>	Apex blackish, often covering more than half of the fruit; base reddish, lighter below
	<i>Virescens</i>	No anthocyanin in exocarp; fruit green when unripe, orange with greenish tip when ripe
Mesocarp colour	<i>Albescens</i>	Very low carotene in mesocarp, which is pale yellow, not orange
Fruit morphology	<i>Poissoni</i> , mantled, diwakkawakka	Fruit surrounded by up to six fleshy 'supplementary carpels', derived from stamen primordia
Fruit forms		
Shell thickness	<i>Dura</i>	Thick shelled: shell 2–8 mm, occasionally less, 35–65% mesocarp/fruit, no fibre ring surrounding nut in cross-section
	<i>Tenera</i>	Thin shelled: shell 0.5–4 mm, 55–96% mesocarp/fruit; fibre ring present
	<i>Pisifera</i>	Shell-less, usually female sterile
Miscellaneous	<i>Gracilinux</i>	<i>Virescens pisifera</i> (Chevalier, 1910)
	<i>Lisombe</i>	<i>Tenera</i> (Preuss, 1902)

developed. A plug of fibre is formed in each germ pore and these fibres are cemented together at the base to form a plate-like structure continuous with the inner surface of the shell (Hussey, 1958).

Inside the shell lies the kernel. This consists of layers of hard oily endosperm, greyish white in colour, surrounded by a dark-brown testa covered with a network of fibres. Embedded in the endosperm and opposite one of the germ pores lies the embryo, about 3 mm in length, with its distal end opposite the germ pore but separated from it by a thin layer of endosperm cells, the testa and the plate-like structure referred to above

(Plates 2.1, IIC). These three structures have been together called the operculum, but they are separate.

In the quiescent state the bud is already well developed laterally within the distal end of the embryo. In longitudinal section the apex with two differentiated leaves and the rudiments of a third can be distinguished, although the radicle (seedling root) is only poorly differentiated (Vallade, 1966). Opposite the bud there is a longitudinal split in the wall of the embryo. This part of the embryo is separated by a small constriction from the cotyledon which will develop into the haustorium. The endosperm above the embryo is

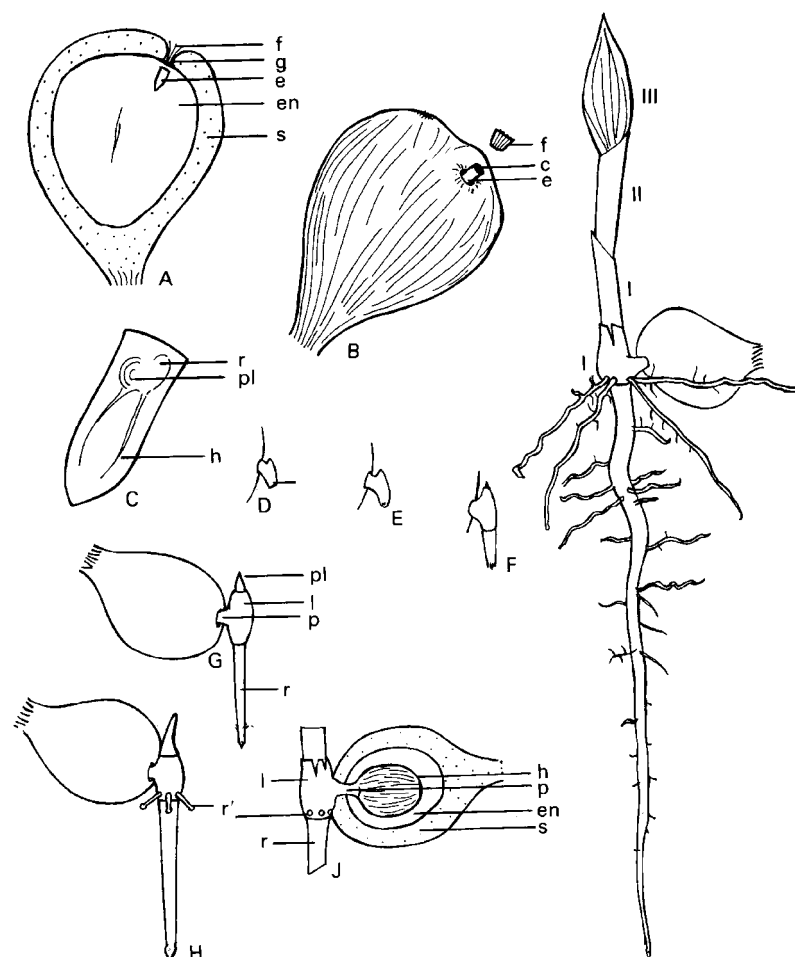


Fig. 2.1 Oil palm seed and early growth of seedling. A: longitudinal section of seed through embryo; B: just germinated seed; C: median longitudinal section of embryo; D, E, F, G: successive stages in the early growth of the embryo; H: production of adventitious roots; I: 4-week-old seedling; J: section of seed to show haustorium; c: cap of testa; e: embryo; en: endosperm; f: fibre plug; g: germ pore; h: haustorium; l: ligule; p: petiole; pl: plumule; r: radicle; r': adventitious root; s: shell; I-III: plumular leaves. [From Rees, 1960, with permission from the Editor, *Palms* (formerly *Principes*)].

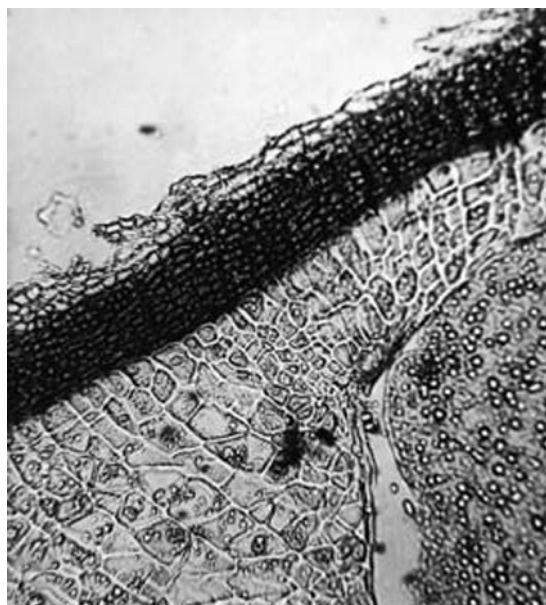


Plate 2.1 Longitudinal section of a *tenera* kernel showing the distal end of the embryo enclosed by the endosperm and dark-coloured testa. Note that the endosperm is continuous above the embryo; rupture will take place through the small cells at the corner (Hussey, 1958).

demarcated by a ring of cells of small size. When germination takes place the endosperm ruptures in this region and a disc consisting of endosperm, testa and the germ-pore plate is extruded from the germ pore together with the fibre plug.

The process of seed germination is illustrated in Fig. 2.1. The emerging embryo forms a 'button' [commonly called the hypocotyl but considered by Henry (1951) to represent the petiole of the cotyledon]. The plumule (seedling shoot) and radicle both emerge through a cylindrical, persistent ligule close to the seed. Inside the seed the haustorium develops steadily. This organ is yellowish and convoluted along the long axis of the nut, thus providing a greater surface area for absorption. Within about 3 months after germination starts, the spongy haustorium has absorbed the endosperm and completely fills the nut cavity (Anon., 1956).

2.2.1.2 The seedling

During the first few weeks of growth, the seedling is entirely dependent on the supply of stored material from the endosperm. Alang *et al.* (1988) found that the endosperm contained 47% fat and 36% galactomannan,

a carbohydrate; the developing seedling utilised the galactomannan before the fat. Boatman and Crombie (1958) showed that 80% of the fat in the endosperm had been used by 3 months after germination, and 98% by 5 months. Some of the stored fat is used in respiration, and the total weight of seed plus seedling decreased by 20% 3 weeks after germination. Tan and Hardon (1976) showed that leaf area in the prenursery was significantly correlated with kernel weight, indicating the importance of the kernel reserves for early growth, but after 6 months in the main nursery the correlation was no longer significant. Oo (1986) discussed the biochemistry of germination in some detail.

The plumule does not emerge from the plumular projection until the radicle has reached 1 cm in length. The first adventitious roots are produced in a ring just above the radicle–hypocotyl junction and they give rise to secondary roots before the first foliage leaf has emerged (Fig. 2.1, H and I). The radicle continues to grow for about 6 months, by which time it has reached about 15 cm in length. Thereafter, numerous primary roots develop in its place.

Two bladeless plumular sheaths are produced before a green leaf emerges. The latter is recognised by the presence of a leaf blade (lamina), and it emerges about 1 month after germination. Thereafter, one leaf per month is produced until the seedling is 6 months old. A 2-month-old seedling is shown in Fig. 2.2. After the first leaf has expanded, photosynthesis starts, and the plant begins to gain weight. Removal of the seed during the first 7 weeks reduced seedling leaf area growth rate (Corley, 1976g); up to that stage the weekly loss in weight of the endosperm was greater than the gain in weight of the seedling. Once the first leaf was fully expanded, the contribution from photosynthesis started to exceed the losses due to respiration, and seed removal thereafter had no detectable effect, indicating that the seedling was no longer dependent on the endosperm reserves.

After 3–4 months the base of the stem becomes a swollen 'bulb' and the first true primary roots emerge from it. These are thicker than the radicle and grow at an angle of 45° from the vertical. Secondary roots grow out in all directions. During this second period in the seedling's life the leaves become successively larger and change in shape. The leaves of the adult palm are pinnate, but this form is only reached in stages. The first few leaves are lanceolate with a midrib to half their length; two veins proceed from the end of this midrib to the tip of the leaf. In later leaves a split appears between these veins and the leaf becomes bifurcate. This type of leaf is quickly followed by leaves in which

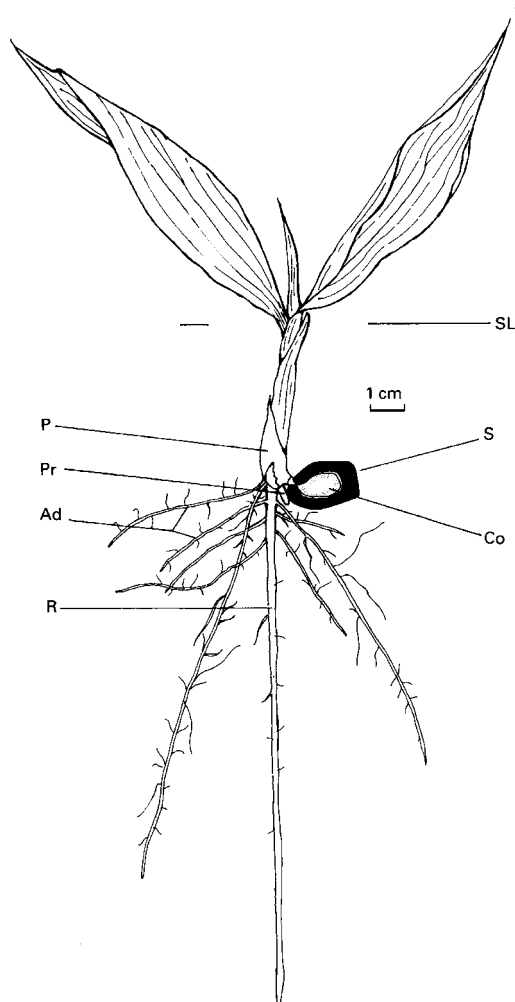


Fig. 2.2 Young seedling 2 months after planting. SL: soil level; S: shell; Co: cotyledon (haustorium); P: plumule; R: radicle; Pr: primary root; Ad: adventitious roots. The nut is shown in section. (From Anon., 1956.)

splits divide the laminae between the other veins into leaflets or pinnae, although the latter are still joined to one another at the apex. Later still the leaflets become entirely free, although when the leaf opens the tip of the leaflet is always the last part to become separated.

Young pinnate leaves differ from mature leaves (described in Section 2.2.1.4) in the following respects: the leaflets are inserted directly on to the midrib, without pulvini; the lower leaflets do not degenerate into spines; they are less xeromorphic than mature leaves, and they have stomata on both upper and lower surfaces.



Plate 2.2 Median longitudinal section through the apex of a young oil palm (Rees, 1964). Note the basin-like depression containing the apical meristem and young, unelongated leaves. The primary thickening meristem is located just above the 5 cm scale indicator.

Henson (1991d) found 92 stomata/mm² on the lower surface, and 17/mm² on the upper surface of leaves of 18-month-old palms.

2.2.1.3 Development of the stem and stem apex

In common with other palms, early growth of the oil palm after the seedling stage involves the formation of a wide stem base, without internodal elongation. According to Jacquemard (1979) there is very little height growth in the first 3 years. Once the internodes begin to elongate a columnar stem is formed. Although each stem segment may be described as an internode plus leaf, the node is only indicated externally on old palms by the leaf scar; internally there is no boundary between adjacent internodes.

The palm has one terminal growing point. Very occasionally branched palms develop with two or more growing points, as a result of damage to the apex resulting in the formation of two or more apical meristems. The separate stems grow vertically, usually close together.

The apical meristem lies in a basin-like depression at the apex of the stem (Plate 2.2). In mature palms this

depression is 10–12 cm in diameter and 2.5–4 cm deep. There are as many as 50 leaves from the centre of the depression to the highest point of the rim. The apex itself is buried in the crown of the palm within a soft mass of young leaves and leaf bases commonly known as the ‘cabbage’, which is edible. The young leaves, which have not yet elongated, are largely composed of leaf bases with lateral extensions. The remainder of the leaf is reduced to small apical corrugations.

The depression in which the apex lies is the result of the peculiar method of primary growth of palms, described by Tomlinson (1961). In contrast to dicotyledonous trees, there is little or no true secondary thickening in palms. Rather, the stem completes its thickening growth before elongation occurs. The apical meristem is largely a leaf-producing meristem. Thickening growth is brought about by the activity of a meristem which is immediately below the apical meristem, and in which cell division is largely in a tangential plane; this is known as the primary thickening meristem. The base of each leaf primordium completely encircles the next youngest leaf, and the bases increase in diameter to keep pace with the activity of the primary thickening meristem. Elongation of the internodes only begins where primary thickening has ended, where the stem has more or less reached its maximum diameter.

During the early years, while the wide stem base is being formed, the base assumes the shape of an inverted cone. It is from this cone that the adventitious primary roots are continually being formed, both below ground and just above it.

The crown of a mature palm consists of between 30 and 50 leaves; in a grove palm the oldest leaves dry up and the rachis snaps; in a plantation palm, old leaves are pruned off. In both cases, though, the leaf bases remain adhering to the stem until the palm is at least 12 years old, sometimes much longer. They eventually fall off quite cleanly, with separation usually starting from the middle of the stem and extending gradually both upwards and downwards. It is not known what triggers this abscission process. When all leaf bases except a few near the crown have been lost, the palm is said to be smooth stemmed instead of rough stemmed. In a palm grove, a palm rarely becomes smooth stemmed until it has grown, at least partially, above the surrounding vegetation and is in bearing. On smooth stemmed palms the leaf base scars remain clearly visible.

The arrangement of the leaves with regard to the axis of the palm is known as phyllotaxis. The leaves are produced at the apex in a pattern which, seen from above, is roughly triangular. A fourth leaf in order of production does not, however, fall into place exactly

above the first since the angle that two successive leaves make with the axis (the divergence angle) averages 137.5°. The arrangement therefore gives rise to sets of spirals or parastichies (Henry, 1955b; Anon., 1961).

In well-grown plants two sets of spirals can be seen, eight running one way and 13 the other. If the leaf bases are numbered in the order of leaf formation (the ‘genetic spiral’) this becomes clear since, one way, every eighth leaf is seen to be in the same spiral while, the other way, every 13th leaf appears in the same (more nearly vertical) spiral. Other parastichies can be seen on the palm; but the larger the parastichy number the more closely it approaches the vertical. The most conspicuous is usually the set of eight foliar spirals, and these may run in either direction, left-handed or right-handed. In two surveys in Malaysia nearly 53% of the palms were left-handed, but there was evidence that this character was not genetically determined (Arasu, 1970a). Several detailed studies of oil palm phyllotaxis have been made (Rees, 1964; Thomas *et al.*, 1969a).

The rate of extension of the stem is very variable, and depends on both environmental and hereditary factors. Under extreme shade or at low temperatures, growth of both leaves and stem is very slow. In dense plantations or secondary bush, the palm will assume an elongated or etiolated appearance, but this is mainly due to elongation of the leaf petioles and rachises. Under normal plantation conditions, and particularly with heterogeneous planting material, there are often marked palm-to-palm differences, but the average increase in height will be from 0.3 to 0.6 m per year. For the cross L2T × D10D in the Ivory Coast, the average height increase was 48 cm/year between 6 and 20 years (Jacquemard, 1979). In high forest, palms may reach a height of 30 m but elsewhere they reach no more than 15 or 18 m. A plantation will normally be replanted when the average height exceeds about 10 m, usually after 25 years or so. The taller the palm, the older it is likely to be; it is not possible to tell the age of individual palms accurately from their height, but it is believed that many grove palms may be 200 years old or more. Of planted palms, one of the original Deli palms at Bogor, Indonesia, still survived in 1992, 144 years after planting (Pamin, 1998), but has since died, possibly from lightning strike (H.L. Foster, pers. comm., 2001).

The diameter of the stem, excluding the attached leaf bases, varies from 20 to 75 cm. In the Deli palm the diameter is said to vary from 45 to 60 cm (Jagoe, 1934) but the stems of ‘Dumpy’ palm progeny are 10–30% wider (Jagoe, 1952a) and 30–40% shorter. In plantations, the stem, after the initial bulge, is usually quite constant in diameter, but uneven stems are commonly

seen in palm groves. This unevenness is due to alterations in shade, in the usage of the surrounding land, and probably also to the scorching of the crown by burning during clearing of the surrounding bush, or to excessive wine tapping.

The stem functions as a supporting, vascular and storage organ. A wide central cylinder is separated from a narrow cortex through which the leaf traces (vascular bundles leading to the leaves) pass. The cylinder has a peripheral zone of congested vascular bundles with fibrous phloem sheaths, and the intervening parenchyma cells are sclerotic; thus, this zone provides the main mechanical support of the stem. The vascular bundles are much less densely packed in the central zone, where most of the storage tissue is located. Starch grains and silica-containing cells are abundant.

The courses taken by the vascular bundles within the stem are relevant to the supply of water and nutrients to the leaves, and of photosynthetic assimilates to the roots. Early workers made some progress in unravelling the vascular system of palms, but a full understanding had to await the imaginative technique of Zimmerman and Tomlinson (1965). Working with the small palm *Rhapis excelsa*, while also examining stems of larger palms, these authors cut serial transverse sections of the stem and photographed them with a cine-camera, using a special arrangement to ensure accurate alignment of successive sections. The resulting film was analysed using a variable speed, reversible, projector. The path that a vascular bundle followed up the stem could be seen as 'movement' when the film was projected.

The general pattern is believed to be essentially similar in the oil palm and other large palms. As it passes up the stem the bundle slants gradually into the central cylinder from the periphery and then bends sharply back outwards, and divides into several branches. One branch forms a leaf trace which continues into the adjacent leaf base; each leaf has many such leaf traces. Other branches may go to the inflorescence peduncle, or form connecting bridges to neighbouring bundles, while another branch bends vertically again to form the continuation of the bundle, and the sequence is repeated. It is this course, being followed by many thousands of bundles, that accounts for the crowding at the periphery and the even but sparser distribution in the centre. In the central part of the stem the bundles follow a spiral course. The ramification of inter-connecting branches between bundles means that all parts of the stem are interconnected; an inflorescence is not solely dependent on the subtending leaf, nor are roots on one side of the palm only connected to leaves on that side.

2.2.1.4 The leaf

In the crown of an adult palm a continuous succession of leaf buds or primordia separates laterally from the apical meristem (Henry, 1955a, c). Development of the leaf is initially very slow. There are some 40–60 leaves within the apical bud (see Section 4.4.3.2); each remains enclosed for about 2 years, then rapidly develops into a central 'spear' and finally opens (Broekmans, 1957b). The base of the developing leaf completely encircles the stem apex and in the adult leaf this leaf sheath persists as a strong, fibrous sheet.

The mature leaf is simply pinnate, bearing linear leaflets or pinnae on each side of the leaf stalk. The latter is divided into two zones, the rachis bearing the leaflets, and the petiole, which is shorter than the rachis, bearing only short lateral spines (Anon., 1962). At the junction of petiole and rachis small leaflets with vestigial laminae are found (Fig. 2.3). Petioles vary greatly in length and may be as long as 1.2 m. The lower (abaxial) surface of the petiole is green, yellowish green or yellow-ochre, sometimes with a darker central stripe, and often with a whitish area at the base. This variation in colouring appears to be genetic, and can be helpful in distinguishing between different clones (see Section 6.4.2). The upper surface of the petiole is greyish. The rachis is similar in colour to the lower surface of the petiole.

The spines are of two kinds, fibre spines and midrib spines (Fig. 2.4). The former are those on the petiole; they are formed from the bases of the fibres of the leaf sheath. The point at which these fibres break off is very regular, so the spines are nearly all the same length. The first leaflets at the base of the rachis are poorly developed, although they have the basal swellings of fully developed leaflets. The lamina of these poorly developed leaflets frequently becomes torn away, leaving a spine which was originally the leaflet midrib (Rees, 1963f).

The leaf stalk or rachis is hard and fibrous, and may be as long as 8 m. At the tip it is almost circular in cross-section, but in the centre of the rachis it is asymmetrical with lateral faces where the leaflets are attached. In the petiole the lateral faces are absent. The lower or abaxial face is much more strongly curved than the upper or adaxial face (Fig. 2.3).

The leaflets are produced by the splitting of an entire leaf during the elongation of the leaf axis. Within the spear the leaflets are still attached to one another, but are folded upwards and show clearly where the splitting will occur.

The number of leaves produced annually by a plantation palm increases to between 30 and 40 at 2–4 years of age. Thereafter, the production declines gradually, to

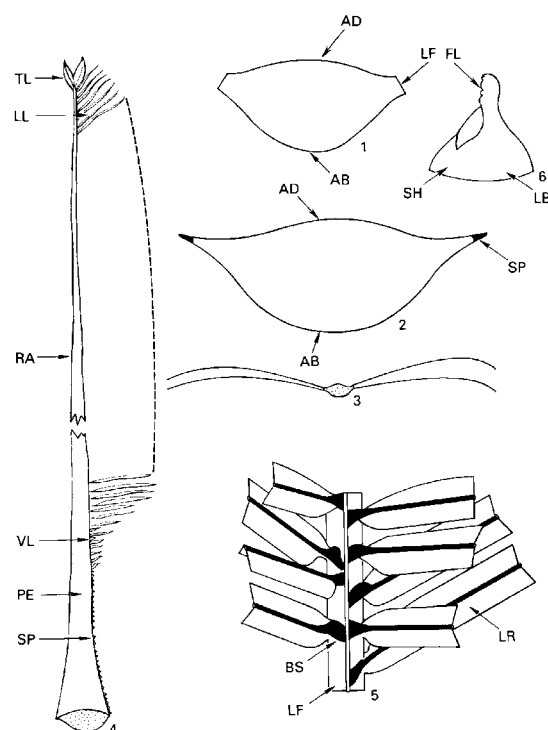


Fig. 2.3 The oil palm leaf. (1) Cross-section of rachis. (2) Cross-section of petiole. AD: adaxial face; AB: abaxial face; LF: lateral face; SP: spine. (3) Cross-section of leaf viewed end-on, showing two-ranked insertion of leaflets. (4) Diagram of oil palm leaf. TL: terminal pair of ovate leaflets; LL: leaflets; RA: rachis; VL: leaflets with vestigial laminae; PE: petiole; SP: spine. (5) Central portion of rachis from above, showing irregular leaflet insertion. BS: basal swelling; LR: lower rank leaflet; LF: lateral face. (6) Developing leaf, enclosed within apex of palm; LB: leaf base; FL: future leaf; SH: leaf sheath completely encircling apex. (From Anon., 1962).

a level of 20–25 per annum from about 8 years onwards (Corley and Gray, 1976a). Leaf production of grove palms is much lower (Zeven, 1967). In an actively growing palm, spears are produced one at a time and point vertically upwards. As the spear opens, another elongates rapidly to take its place. In severe drought, however, several spears may elongate before the oldest opens, so that half a dozen or more nearly fully elongated spears protrude from the centre of the crown. As soon as wet weather ensues the majority of these spears will open in a flush, giving the upper part of the crown a light green appearance for a short period.

After the leaf has opened it is progressively displaced outwards and downwards as younger leaves

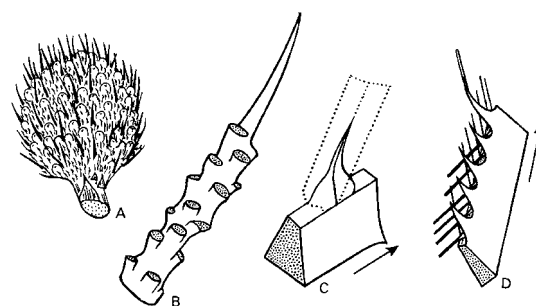


Fig. 2.4 Spines in the oil palm. (A) Fruit bunch with spiny spikelet tips and bracts; (B) single branch of inflorescence with fruit removed; (C) midrib spine, leaflet shown by dotted outline; (D) fibre spines viewed from abaxial side. The arrows in C and D point to the leaf tip. [From Rees, 1963f, with permission from the Editor, *Palms* (formerly *Principes*)].

emerge. Middle-aged leaves lie parallel to the ground with the tip bending slightly downwards. Usually the adaxial face of the rachis faces upwards, but sometimes the leaf tip twists into a vertical plane or even an inverted position.

Typically, the leaflets inserted on the lateral faces alternate in upper and lower ranks, but there is no exact regularity, and two or more consecutive leaflets may appear in the same rank. Similarly, within each rank the angle of insertion is often irregular, and occasionally there is almost no ranking effect. In general, however, it is the existence of two ranks and the irregularity of leaflet insertion that gives the palm its particular appearance, and distinguishes it, at a distance, from the coconut palm or *E. oleifera*. Individual leaflets are linear in shape and each leaf has a terminal pair of leaflets. Leaflets number some 250–300 per mature leaf and are up to 1.3 m long and 6 cm broad. The leaflet midrib is often very rigid and the laminae sometimes tear backwards from the tip. This increases the untidy appearance of the leaf. There is a small basal swelling, resembling a pulvinus but with no motor function, at the insertion of the leaflet on the rachis.

During drought the palm does not wilt. The leaf has a high proportion of lignified tissue and the cells of the epidermis have a thick cuticle and overlie a hypodermis, which is more highly developed on the upper or adaxial surface. The stomata are on the lower or abaxial surface; in Nigeria, a mean density of 146/mm² was recorded (WAIFOR, 1956) and in Malaysia, 175/mm² (Henson, 1991d). They are semi-xeromorphic, with a structure adapted for the prevention of desiccation over long periods of drought. The guard cells of the



Plate 2.3 The *idolatrica* palm, with fused leaflets.

stomata are thick walled with external thickened ridges that lie pressed together for their whole length when the stomata close; at the same time subsidiary cells meet between the guard cells and the stomatal cavity.

Apart from the leaflet variation noted above, more striking leaf variations are to be found. In the *idolatrica* palm the leaflets do not separate normally and an entire or semi-entire leaf is formed (Plate 2.3). The midribs of all the unseparated 'leaflets' are in one plane. The inheritance of the *idolatrica* character is discussed in Chapter 5. Observations have suggested that the centre of distribution of the *idolatrica* palm lies between Ghana and the lower Niger, with many of these palms in Benin and western Nigeria. Westwards and eastwards specimens are rarer and are often found only in botanic gardens or agricultural stations (Hartley, 1988).

Other leaf peculiarities occur but have not been much studied. They may be due to genetic, nutritional or pathogenic factors. Some are described in other sections of this book.

In the axil of each leaf there is a bud which develops into an inflorescence. Rare cases have been known, however, in which a vegetative shoot is produced instead of an inflorescence. This was termed 'vivipary' by Henry (1948a), who described a palm at Okeita, Benin, the shoots taken and developed from it, and similar palms in the Ivory Coast. While in some cases the shoots from 'viviparous' palms can be rooted and will produce similar viviparous palms, in other cases no roots are formed

and sexual buds are later produced either on the palm itself or at the extremity of the axillary shoot. In the latter cases there are also considerable malformations of both the vegetative and sexual parts of the shoots (Henry and Scheidecker, 1953; Davis, 1980).

2.2.1.5 The root system

The seedling radicle grows at a rate of about 4.4 mm/day, to a maximum length of about 50 cm (Jourdan and Rey, 1997c). About a month after germination, the first adventitious primary roots emerge from the radicle-hypocotyl junction, and later from the lower internodes of the stem which are formed into a massive basal cone or bole. The latter retains the capacity for producing roots well above ground level. Roots sometimes develop on the stem up to 1 m above ground, but these normally dry out before reaching the soil.

In the mature palm thousands of primary roots spread from the bole, with new primaries continually replacing dead ones (Yampolsky, 1922). The vertical extent of the root system depends partly on the presence or absence of a water table. Two extremes may be cited. In Malaysia, Lambourne (1935) studied the roots of 11-year-old palms growing in soil where the water table was only 1 m below the surface in dry weather. In these circumstances no primaries penetrated below this depth and the majority of roots were in the surface 45 cm, suggesting that the roots do not penetrate below the level of a permanent water table. In contrast, in free-draining soils primary roots may descend to much greater depths. In Nigeria, Vine found roots down to nearly 3 m (quoted by Purvis, 1956), while Jourdan and Rey (1997c) observed primary roots extending to a depth of 6 m in the Ivory Coast. This unimpeded root system is described below.

Primary roots, 5–10 mm in diameter, extend either downwards from the base of the palm or outwards in a more or less horizontal direction (Fig. 2.5). Although primary roots emerge from the base of the stem at all angles, most authors indicate a distinction between vertical and horizontal roots, with little in between (e.g. Ruer, 1967b). The descending primaries, which proceed directly from under the base of the palm, are fewer in number than the surface primaries and carry fewer secondaries. Ruer (1969) showed that the descending roots played some part in the absorption of water: when they were cut, stomatal opening was significantly reduced. If all primary roots except for the deep roots were cut, however, the stomata remained almost completely closed, so the surface roots appeared more important for water uptake.

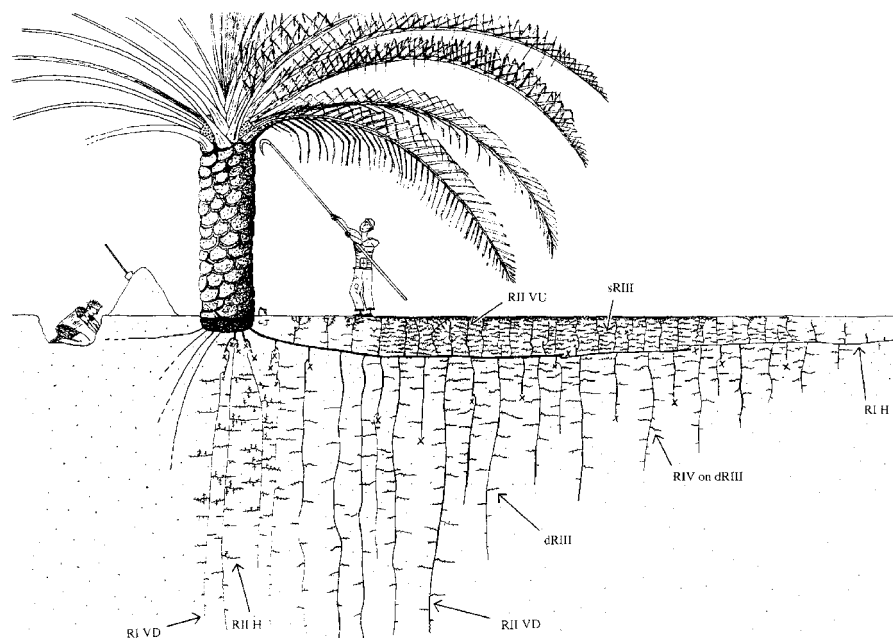


Fig. 2.5 Distribution of roots from one primary root in a 10-year-old palm. The harvesting pole measures 3.5 m. The codes for the root types are: RI: primary; RII: secondary; sRIII: surface tertiary, usually highly branched; dRIII: deep tertiary, less branched; RIV: quaternary; VD: vertical descending; VU: vertical, ascending; H: horizontal. Death of the root apex is indicated by x. (From Jourdan and Rey, 1997c.)

Secondary roots, 1–4 mm in diameter, branch from the primary roots, growing both downwards and upwards, with a slight preponderance of ascending roots. The ascending secondaries generally reach the surface of the soil while the descending ones may penetrate to a depth of several metres. The secondaries give rise to tertiaries, 0.5–1.5 mm in diameter and up to 20 cm in length. According to Jourdan and Rey (1997c), tertiary roots show no preferred direction of growth. From them are developed quaternaries of up to 3 cm in length and only 0.2–0.5 mm in diameter. Henson *et al.* (1994) observed root growth rates of 1.5, 0.75 and 0.3 mm/day for primary, secondary and tertiary roots, respectively. Jourdan and Rey (1997c) measured slightly higher growth rates, of 3, 2 and 0.8 mm/day for primaries, secondaries and tertiaries. Jourdan *et al.* (2000) described anatomical features of the different orders of root in relation to the perception of gravity and direction of growth.

The density (g/m³ of soil) of all classes of roots in the top 60 cm of soil usually decreases with distance from the palm, but with adult palms the total dry weight of absorbing roots in successive surrounding circles increases at least to a radius of 3.5–4.5 m (Ruer, 1967a).

Lambourne (1935) found individual primaries to a distance of 19 m from the stem and absorbing roots at all intermediate distances. Zaharah *et al.* (1989) showed that palms could take up radioactive phosphate from as much as 36 m away, so some roots must extend at least that far from the palm. The greatest quantity of roots is to be found between soil depths of 20 and 60 cm, and most of the absorption of nutrients has been shown to be through the quaternaries and absorbing tips of primaries, secondaries and tertiaries to this depth (Taillez, 1971). However, the exact depth of root concentration depends on the soil type (Chan K.W., 1977).

Roots of all classes show preferential growth towards superior conditions of water and nutrient supply and, with rotting felled vegetation or heaps of palm leaves, or under a good *Pueraria* cover, this may lead to a high density of quaternaries in the centre of the interline (Bachy, 1964). For instance, with a *Pueraria* cover and on good alluvial soil in Colombia tertiaries and quaternaries increased with distance from the palm, but where there was a grass cover the quantity of these roots declined with distance (Hartley, 1988). Similarly, the quantity of roots was much reduced under the paths along the lines. Where the rooting volume is

reduced by quantities of concretionary gravel the quantity of roots per palm is reduced (Tan, 1979), primary roots tend to become twisted and constricted, the root system lies nearer the surface and the tertiaries and quaternaries are coarser and more lignified (Taillez, 1971). Subaerial roots which grow up into loose decaying leaves are readily produced.

The anatomy of palm roots was described by Tomlinson (1961) and that of the oil palm in particular was studied by Purvis (1956) and Ruer (1967b), and more recently by Jourdan and co-workers (Jourdan and Rey, 1997c; Jourdan *et al.*, 2000). The primary root consists of an outer epidermis and lignified hypodermis surrounding a cortex with well-developed air spaces (lacunae) (Plate 2.4a). Within the cortex lies the central stele or vascular cylinder consisting of the surrounding lignified endodermis, 34–45 vascular bundles, and the pith or medulla which rapidly lignifies in old roots. The stele also contains lacunae. The secondary and tertiary roots have essentially the same structure as the primary roots, but with 15–25 and 8–12 vascular bundles, respectively (Jourdan and Rey, 1997c). The unligified tips of growing primary, secondary and tertiary roots measure 3–4, 5–6 and 2–3 cm, respectively. The quaternary roots are only 1–3 cm long, and are almost wholly unligified; there are no root hairs (Plate 2.4B, C). Oil palm roots are usually infected by mycorrhizal fungi (vesicular–arbuscular mycorrhiza) (Morton, 1942; Nadarajah, 1980). The hyphae of these fungi ramify between the cells of the roots, and also extend into the soil, where they play an important role in the uptake of nutrients, particularly phosphate. Zin *et al.* (1996) reported an improved yield after inoculating palms on peat with mycorrhiza.

The roots of *E. guineensis* (and other palms) are characterised by the presence of pneumatodes on both underground and aerial roots. These have been supposed to ventilate the underground roots, but direct physiological evidence for this is lacking. Yampolsky (1924) found more pneumatodes on aerial than on underground roots in Sumatra, but the reverse is the case in West Africa. Moreover, they are most common on seedlings grown in glasshouses or wherever the root system has been kept under water or in very moist conditions (Purvis, 1956).

In pneumatode-forming roots the epidermis and hypodermis rupture and the stele and cortex extrude. The latter then proliferates and its parenchymatous cells become suberised (corky) or, if the pneumatode is aerial or subjected to dry conditions, lignified (Plate 2.4D). If the growing point is unharmed after the rupture of the epidermis it remains attached as a cap and sometimes a normal root may develop again.

It is the ability of roots to absorb nutrients and water that is important, and this is related to the total length of root per unit volume of soil (Tinker and Nye, 2000). There is little information on length of oil palm root systems, but Tinker (1976) estimated a total length of 32,000–45,000 m/palm for 4½–6½-year-old palms.

2.2.1.6 Oil palm chromosomes

The genus *Elaeis* has 16 pairs of chromosomes (diploid number, $2n = 32$). Tan (1976) illustrated chromosomes at various stages of cell division. Maria *et al.* (1995) assigned the chromosomes to three groups, differing in length, there being one long pair, eight medium-length pairs and seven short pairs. Castilho *et al.* (2000) used fluorescent labelling techniques to distinguish chromosomes within the groups (Plate VIC). *Elaeis oleifera* chromosomes are similar to those of *E. guineensis* (Maria *et al.*, 1998), but Cheah *et al.* (2000) showed that fluorescent labelling could be used to distinguish *E. oleifera* chromosomes under the microscope in crosses between the two species.

2.2.2 Flowering and fruiting

Inflorescence development is described briefly here; the stages in development, and responses to environmental and other factors, are discussed in more detail in Chapter 4.

2.2.2.1 Inflorescences

The oil palm is monoecious; that is, male and female flowers occur separately on the same plant, usually in distinct male and female inflorescences (Plates 2.5, IB, C). Detailed investigation of the flowers has shown, however, that each flower primordium includes both male and female organs (Beirnaert, 1935b). In rare cases both develop fully, to give a hermaphrodite flower. An inflorescence is initiated in the axil of every leaf but some inflorescences abort before emergence. Rarely, twin inflorescences are found in a single leaf axil. An inflorescence can be male, female or mixed. The first inflorescences produced by young palms are usually male, but thereafter the order and proportions in which inflorescences are produced show little or no regularity. Mixed inflorescences, with both male and female spikelets, are more common in young palms (Section 2.2.2.4).

Each inflorescence consists of a stout peduncle 30–45 cm in length, with spikelets arranged spirally around it in a manner which varies both with age and

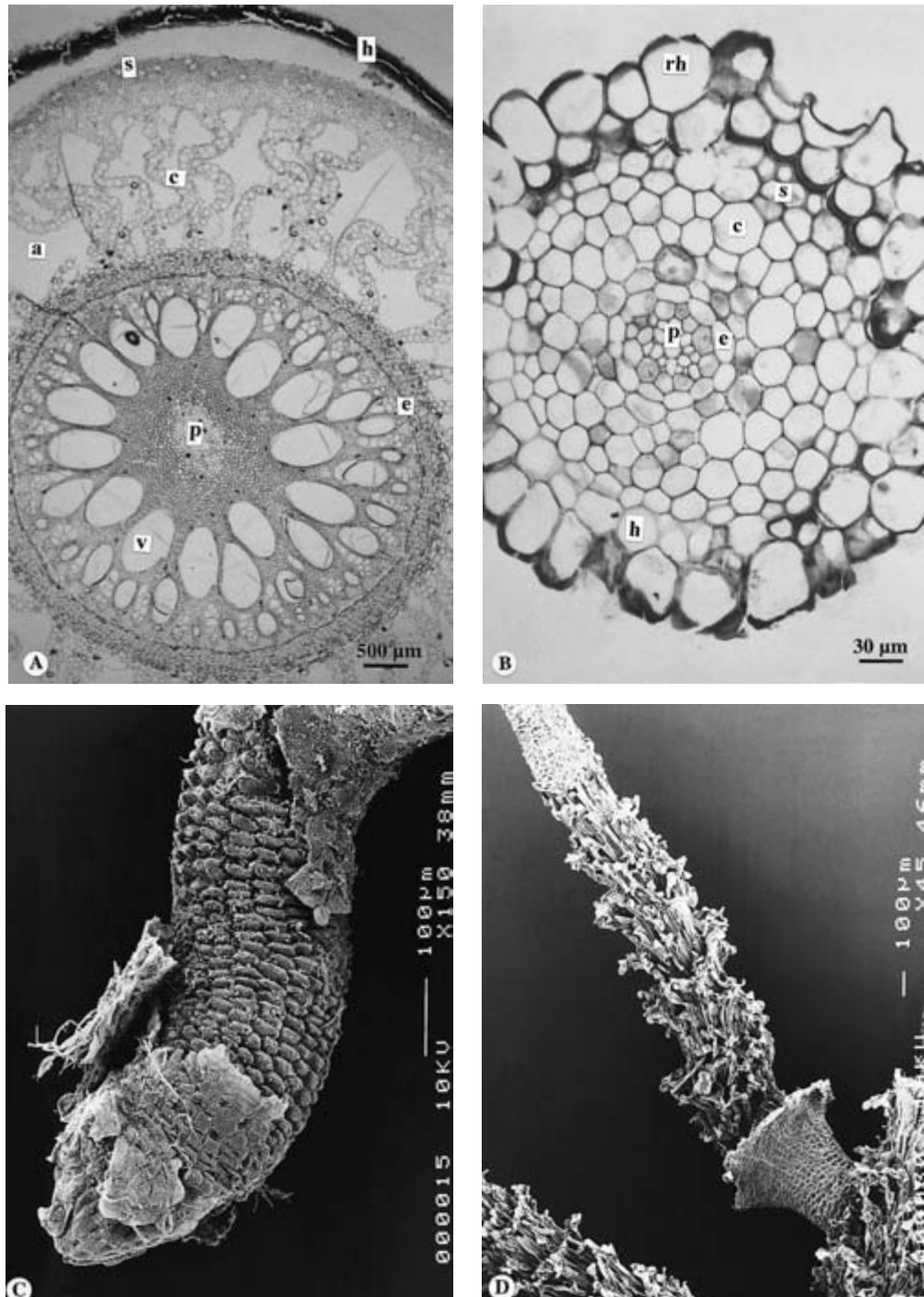


Plate 2.4 Anatomy and morphology of oil palm roots. (A) Cross-section of primary root. (B) Cross-section of quaternary root. (C) Scanning electron micrograph of tip of quaternary root. (D) Scanning electron micrograph of pneumathode. a: aerenchyma; c: cortex; e: endodermis; h: hypodermis; p: pith; rh: rhizodermis; s: sclerenchyma; v: medullary vessel. (From Jourdan and Rey, 1997c.)



Plate 2.5 Male and female inflorescences at two stages of development. (A) Before anthesis, within (left) and freed from (right) the spathes. (B) At anthesis. Below: some abnormal pollen-producing flowers at the ends of female spikelets. (Unilever Ltd.)

position on the rachis. Phyllotaxis measurements have shown little difference between male and female inflorescences (Thomas *et al.*, 1970). For most of its development, the inflorescence is completely enclosed in

two fibrous spathes. About 6 weeks before anthesis, the outer spathe splits; after a further 2 or 3 weeks the inner spathe also splits, and later both spathes fray and disintegrate, exposing the inflorescence.

Van Heel *et al.* (1987) followed inflorescence development by scanning electron microscopy from a very early stage (Plate 2.6); the recognisable developmental stages are also discussed in Chapter 4, in relation to the

determination of yield components. Initially, four bracts are formed on the peduncle, two of which will extend nearly to the top of the mature inflorescence (Plate 2.6A). There follows a period during which spi-

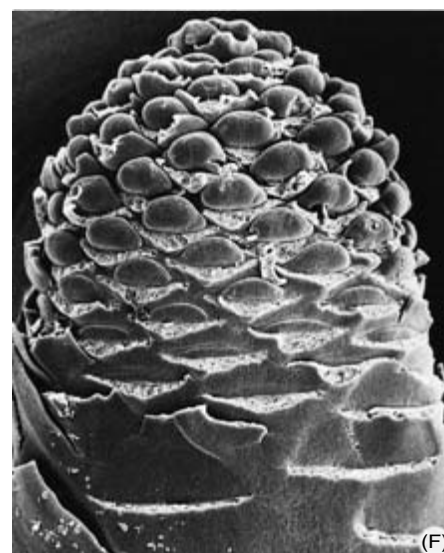
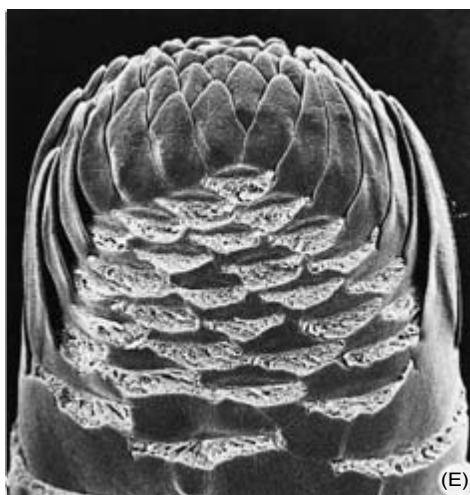
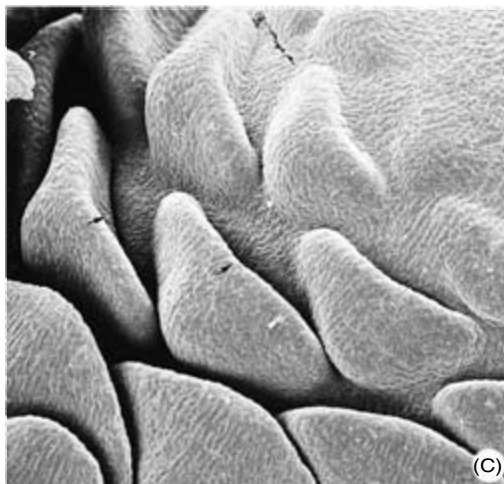
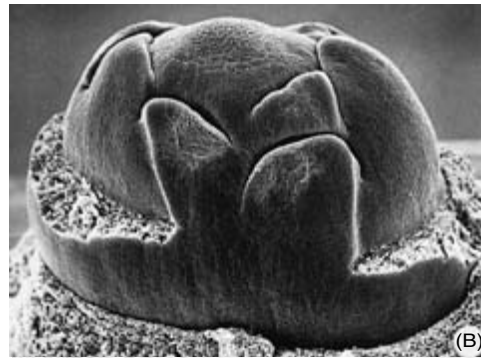
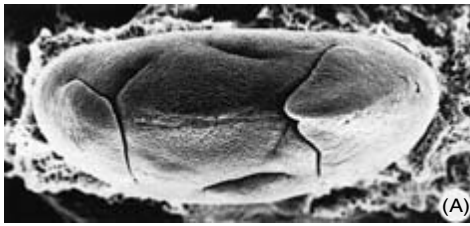


Plate 2.6 (see opposite)

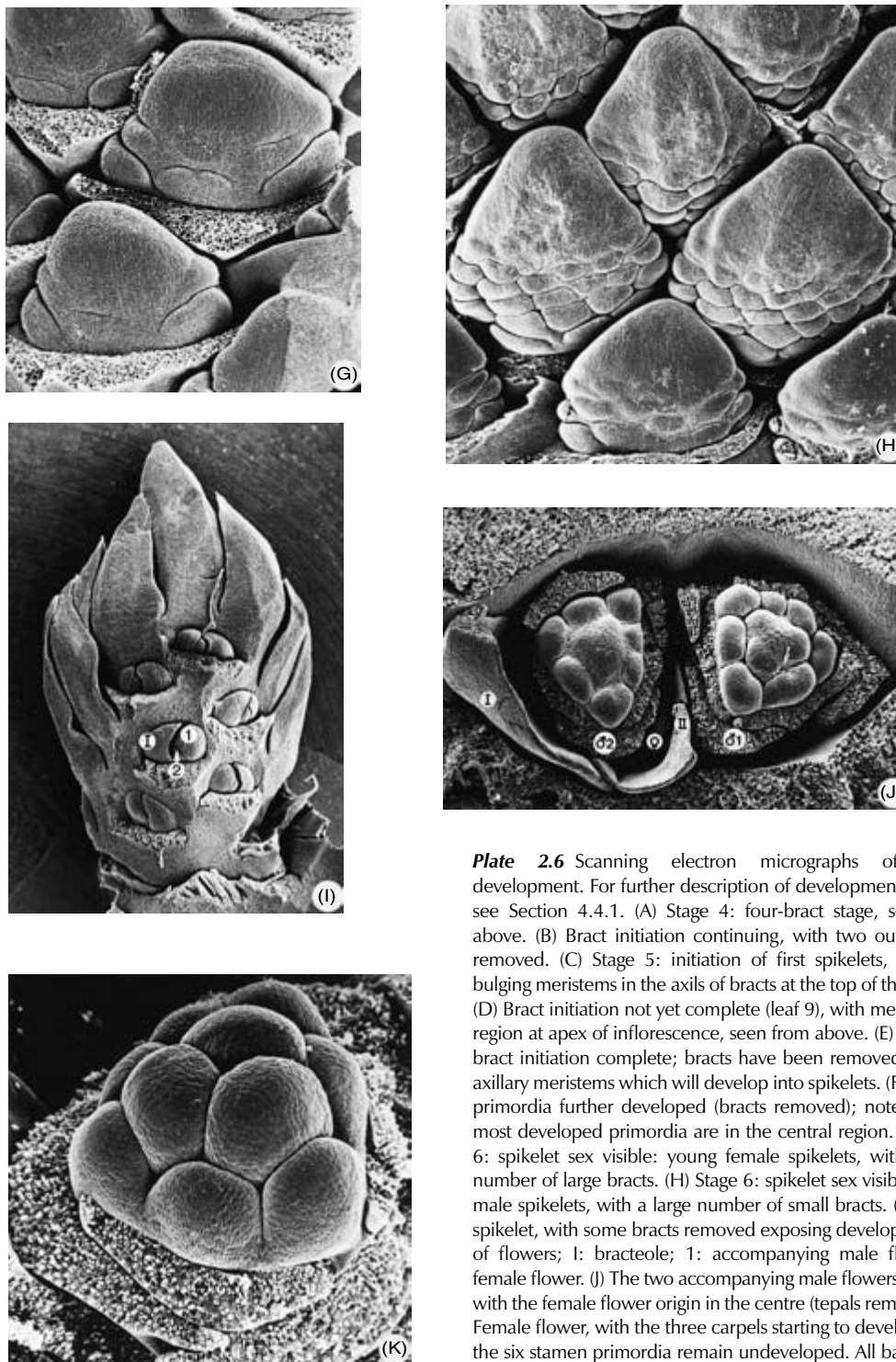


Plate 2.6 Scanning electron micrographs of flower development. For further description of developmental stages, see Section 4.4.1. (A) Stage 4: four-bract stage, seen from above. (B) Bract initiation continuing, with two outer bracts removed. (C) Stage 5: initiation of first spikelets, visible as bulging meristems in the axils of bracts at the top of the picture. (D) Bract initiation not yet complete (leaf 9), with meristematic region at apex of inflorescence, seen from above. (E) Stage 5a: bract initiation complete; bracts have been removed to show axillary meristems which will develop into spikelets. (F) Spikelet primordia further developed (bracts removed); note that the most developed primordia are in the central region. (G) Stage 6: spikelet sex visible: young female spikelets, with a small number of large bracts. (H) Stage 6: spikelet sex visible: young male spikelets, with a large number of small bracts. (I) Female spikelet, with some bracts removed exposing developing triads of flowers; 1: bracteole; 1: accompanying male flower; 2: female flower. (J) The two accompanying male flowers of a triad with the female flower origin in the centre (tepals removed). (K) Female flower, with the three carpels starting to develop, while the six stamen primordia remain undeveloped. All bars except on I represent 0.1 mm. (From van Heel *et al.*, 1987.)

rals of bracts are formed. The development of spikelet primordia in the axils of all but the basal six to ten of these bracts then starts, somewhat below the apex of the inflorescence (Plate 2.6B). The number of spikelets per inflorescence varies greatly from palm to palm, but Beirnaert (1935a) showed that the variation between inflorescences of a given palm is small and is independent of the sex of the inflorescence. In 37 adult palms in Congo the average number of spikelets per inflorescence was found to range from 100 to 283 and in most cases the coefficient of within-palm variation was very small. In mixed inflorescences the sum of the male, female and mixed spikelets was close to the average number of spikelets for male or female inflorescences of the palm concerned. Corley and Gray (1976b) showed that average spikelet number increased with palm age, from an average of about 60 in 3-year-old palms to 150 by 10 years.

The development of male and female inflorescences appears identical up to the point where bracts are initiated on the spikelet primordia. As on the peduncle, four bracts are formed initially at the base of each spikelet, followed by the bracts which will subtend the flowers. After this point, the sex is easily distinguished, with male spikelets producing a very much larger number of floral bracts (Plate 2.6E, F).

2.2.2.2 The female inflorescence and flower

The female inflorescence (Plate IC) reaches a length of 30 cm or more before opening. The flowers are arranged spirally around the rachis of the spikelet, each in a shallow cavity and subtended by a bract; these bracts develop into sharp spines, which may project from the ripe bunch, making it very difficult for the harvester to handle. The end of the spikelet also forms a spine, of variable length, but these are usually fairly blunt, unlike the bract spines. The number of flowers in an inflorescence varies from palm to palm; there is a larger number (12–30) on the central spikelets than on the lower or upper spikelets (12 or fewer). Corley and Gray (1976b) found an average of about ten flowers per spikelet in 3-year-old palms, increasing to over 15 after 10 years. The inflorescence will thus contain anywhere from a few hundred to several thousand flowers, depending mainly on palm age.

The functional female flower develops in a triad between two non-functional ‘accompanying male’ flowers (Plate 2.6I, J). This was first described by Beirnaert (1935b), and in more detail by van Heel *et al.* (1987) (Fig. 2.6). The female flower is enclosed by a

double perianth of six sepaloid segments in two whorls; these in turn are enclosed by two bracteoles. The sessile stigma has three lobes; these are hairy, with a crest forming the receptive surface (Lawton, 1982), and they exude moisture at the receptive stage. The sessile stigma has three papillate lobes; before anthesis these are pressed together, but they open to expose their moist inner surfaces at the receptive stage. Lawton (1982) described the receptive surface as forming a crest, but Tandon *et al.* (2001) showed that there is a deep groove running down the centre of each lobe, with a well-defined layer of glandular cells forming the sides of the groove. The sepals are about 2 cm long. The rudimentary stamen primordia form a ring around the base of the flower, with six, or sometimes more, short projections (Plate 2.6K).

Beirnaert (1935b) described in detail the range of development of the rare hermaphrodite flowers which may occur on both male and female inflorescences. Occasionally two female flowers may develop, within a single pair of bracteoles, between the two accompanying male flowers. The accompanying male flowers sometimes develop normally, producing pollen (Plate 2.5B). Abnormalities such as these must be taken into account by plant breeders doing controlled pollinations.

Anthesis in a normal inflorescence usually lasts for 36–48 h but may be extended to a week. The flowers on spikelets at the base of the inflorescence open before those at the top and, within each spikelet, those at the base open first. After anthesis, the stigma lobes turn purplish with anthocyanins, and Tandon *et al.* (2001) showed that pollen did not germinate on stigmas which had undergone this colour change.

2.2.2.3 The male inflorescence and flower

The male inflorescence (Plate IB) is borne on a longer peduncle than that of the female inflorescence and contains long, finger-like, cylindrical spikelets. It is not spiny; the spikelet has short bracts and a short terminal projection. Spikelets measure 10–20 cm in length and 0.8–1.5 cm in breadth.

Before opening, the sessile flower is completely enclosed by a triangular bract; it consists of a perianth of six minute segments, a tubular androecium with six, or rarely seven, anthers, and a rudimentary gynoecium with three projections corresponding to the trilobed stigma. The flower is solitary, but is considered to correspond to the first male flower of the triad found in female inflorescences (van Heel *et al.*, 1987). The three outer perianth segments are hard, the inner ones soft. The flower is 3–4 mm long and 1.5–2.0 mm wide.

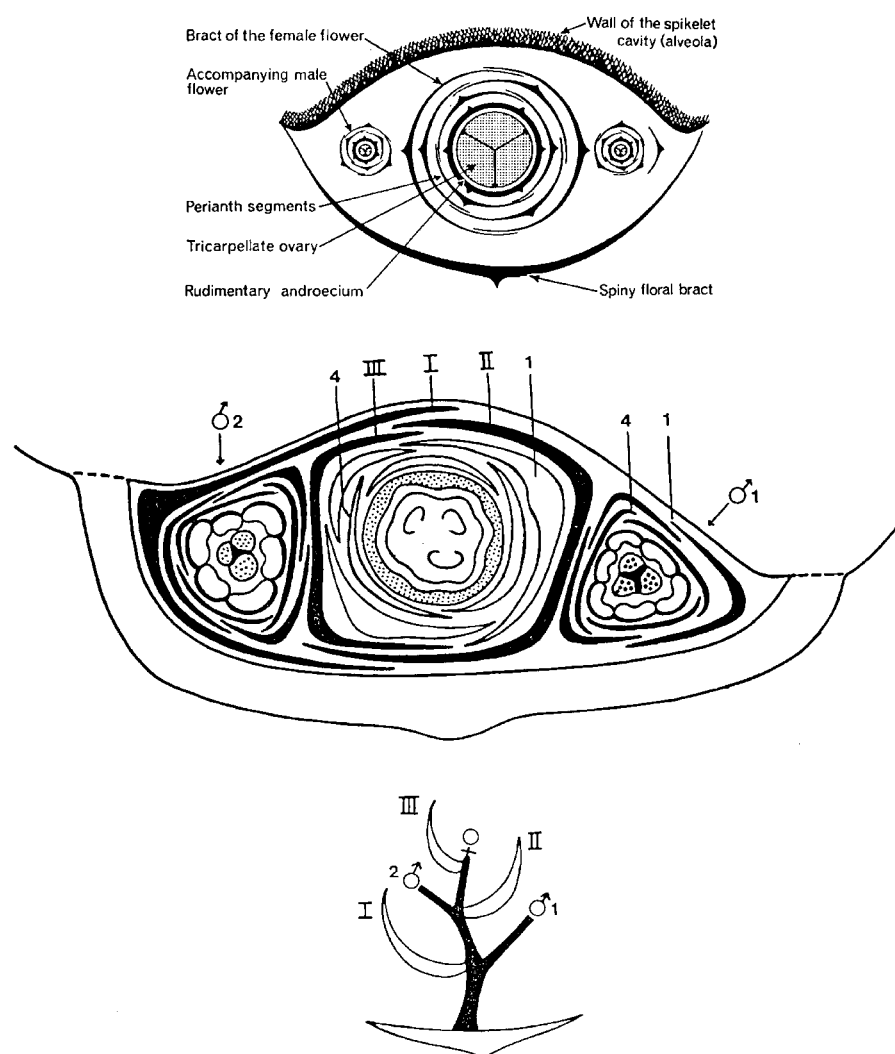


Fig. 2.6 Diagrams of the female flower with accompanying rudimentary male flowers. (1) Floral diagram. (From Beirnaerst, 1935b.) (2) Floral diagram. (From van Heel et al., 1987) (3) Diagram of branching system (van Heel et al., 1987.)

Spikelets of 8-year-old *tenera* palms in Malaysia were found to have an average of 785 flowers (Tan and Rao, 1979); with about 150 spikelets, there would thus be well over 100,000 flowers per inflorescence.

Anthers of the male flowers dehisce by vertical slits. The pollen grains are at first oval, but at maturity they are two-celled and somewhat triangular in outline (Tan and Rao, 1979). Flowers begin to open from the base of the spikelet and all flowers on the spikelet have usually opened within 2 days, although during rainy weather opening may be prolonged to 4 days. Most pollen is shed during 2 or 3 days following the start of anthesis

and production ceases within 5 days. Pollen remains viable for at least 6 days after release (Hardon and Turner, 1967), but viability of pollen produced towards the end of the anthesis period may be low. One inflorescence produces from 25 to 100 g of fresh pollen.

2.2.2.4 Mixed inflorescences

A variety of mixed inflorescences may be formed; Williams and Thomas (1970) illustrated some of these. Male, female and mixed spikelets may appear on the same bunch, in varying proportions and positions.

Some palms are more disposed to the production of these inflorescences than others. The mixed spikelets have female flowers at the base and male flowers at the apex. In between there may be pairs of male flowers, corresponding to the accompanying male flowers, lying close together with no female flower between them (Beirnaert, 1935b). Further up the spikelet these give way to the normal single male flowers. Spikelets can contain either all three types of flower group, or male flowers only in singles and pairs, or they may have the superficial appearance of a female spikelet but contain pairs of male flowers.

Young palms occasionally produce a peculiar type of inflorescence which has been called 'andromorphic'. This has the appearance of a male inflorescence before it opens, but the male flowers are replaced by small, solitary female flowers arranged in the manner of flowers in a male inflorescence. Small, usually parthenocarpic, fruit may develop from the flowers, but the carpels are often not firmly joined together and the resulting fruit have three lobes corresponding to the three partially separated carpels. Male flowers may also be found in andromorphic inflorescences, although some are deformed. Williams and Thomas (1970) described andromorphic inflorescences as being produced during a change from a female to a male phase in the flowering cycle, but this is not true for young palms.

2.2.2.5 Pollination

For a long time it was thought that the oil palm was mainly wind pollinated, and that pollination failures were caused by a low proportion of male inflorescences and unfavourable atmospheric conditions within the plantation. The early authorities such as Lespesme (1946), Alibert (1945) and Beirnaert (1935b) believed that insects were not required for pollination, although Henry (1948b) thought that they may play some part. These views held firm for more than 40 years and led to much work being done on the wind movement of pollen and methods of assisted pollination.

Syed (1979, 1982) showed that the early views were wrong: he found that the palm was mainly insect pollinated, and that wind played relatively little part in pollination in either Malaysia or Cameroon, particularly during the rainy season in the latter country. Numerous species are involved in pollination of oil palms in Cameroon, but the main pollinating agents are from a subfamily of weevils, the Derelomini, among which species of *Elaeidobius* predominate (Plate 2.7A, B). The Derelomini are also involved in pollination of numerous other

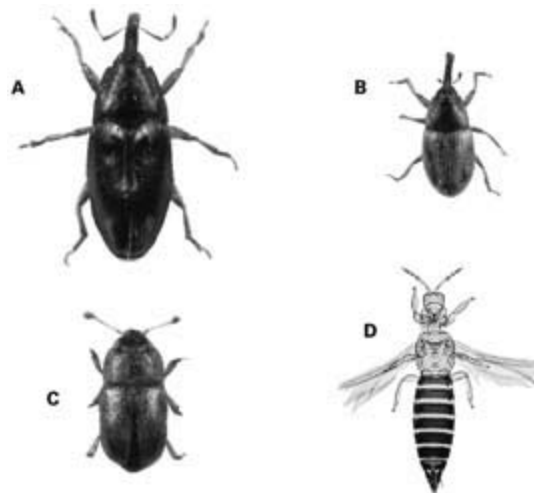


Plate 2.7 Insect pollinators of the oil palm. (A) *Elaeidobius kamerunicus* (Curculionidae), Africa, male ($\times 10$). (B) *Elaeidobius subvittatus*, Africa, female ($\times 10$). (C) *Mystrops costaricensis* (Nitidulidae), South America ($\times 16$). (D) *Thrips hawaiiensis*, Asia ($\times 24$). (By courtesy of the Trustees of the British Museum of Natural History.)

palm species (Henderson, 1986a). These weevils feed on the soft parts of male flowers and on pollen, and lay their eggs on male flowers. Female inflorescences have the same aniseed scent as males, and the weevils apparently visit them only by accident in the search for male inflorescences (Syed, 1979). An individual weevil remains for a very short time on the female inflorescence, which probably explains why their role was not recognised earlier.

The genus *Elaeidobius* was absent from South-east Asia, and in Malaysia the main pollinator was *Thrips hawaiiensis* (Syed, 1979) (Plate 2.7D); this species was usually absent from young plantings, explaining why assisted pollination was required. In Sabah, although *T. hawaiiensis* was present, it had apparently not adapted to the oil palm and did not contribute to pollination, but some pollen was dispersed by a moth, *Pyroderces* sp. (Syed, 1979; Tan and Basri Wahid, 1985).

Thrips hawaiiensis was not a very efficient pollinator, and Syed (1982) considered that *Elaeidobius kamerunicus* could usefully be introduced to Malaysia. Syed (1982) and Kang and Zam (1982) showed that *E. kamerunicus* was unable to complete its life cycle on any species except for *Elaeis guineensis*, and thus there would be no ecological risk in introducing it to South-east Asia.

Kang (1999) tells the story of the introduction: the weevil was released on two plantations in Malaysia in February 1981, and population increase and spread were very rapid (Syed *et al.*, 1982). Later there were releases in Indonesia, Papua New Guinea and Colombia. The consequences in terms of improved fruit set are discussed in Section 4.4.7.1.

In Latin America two pollinating beetles have been found on both *E. guineensis* and *E. oleifera*. These are the sap beetle, *Mystrops costaricensis* (Plate 2.7C), which is common in areas of high, even rainfall, and the weevil, *Elaeidobius subvittatus*, a native of Africa which is thought to have been fortuitously introduced, perhaps transported in pollen samples (Wood, 1983b). However, the exact status of these two insects, and the reasons for their uneven distribution, are not fully understood. Fruit set in America, although generally better than in Asia before the introduction of *E. kamerunicus*, was not always satisfactory until *E. kamerunicus* was introduced (Syed, 1984; Corrado, 1985). Since the introduction, populations of *E. subvittatus* and *M. costaricensis* have diminished (Chinchilla and Richardson, 1990).

2.2.2.6 The fruit

A short description of the morphology of the fruit is given here (Plate IIC). Some of the terms used to describe different fruit forms are listed in Table 2.1. Fruit variation and the inheritance of fruit characters are discussed more fully in Chapter 5.

The fruit is a sessile drupe varying in shape from nearly spherical to ovoid or elongated and bulging somewhat at the top. In length it varies from about 2 cm to more than 5 cm, in weight from 3 g to over 30 g. The Deli fruit of the Far East tend to be larger than most, although fruit as large as Deli fruit are sometimes encountered in Africa. The pericarp of the fruit consists of the outer exocarp or skin, the mesocarp or pulp (often incorrectly termed the pericarp) and the endocarp or shell. When measuring the pulp, the exocarp is included with the mesocarp. The endocarp together with the kernel forms the seed, described above.

There is one abnormal fruit type, variously known as *Poissoni*, mantled or *dimakkawakka*, in which fleshy outgrowths or supplementary carpels surround the main part of the fruit. These have developed from the rudimentary stamen primordia of the female flower, but they are considered to be carpellary in character since they are often found to contain shell and kernel in the centre (Fig. 2.7, Plate VIIC, D). Mantled fruit are rare; in one area of Nigeria only 33 mantled bunches were found from among 20,291 bunches harvested



Fig. 2.7 Longitudinal sections of mantled fruit. Left: after Beirnaert (1935b); right: after Janssens (1927), with one of the supplementary carpels showing complete development.

from grove plots over a 4-year period. In Angola the frequency was found to be nine palms in 10,000. Similar figures have been quoted elsewhere (Zeven, 1973). Fruit apparently identical to the *Poissoni* type may be produced by clonal palms propagated by tissue culture. This abnormal development is often followed by complete bunch failure, which up to the time of writing has prevented the commercialisation of clonal propagation on anything but a trial scale (see Section 6.3.1).

Fruit colour: In external appearance the normal fruit varies considerably, particularly when ripening. Moreover, the exocarp of the fruit on the outside of the bunch tends to be more pigmented than that of the internal fruit. The most common type of fruit is deep violet to black at the apex and pale greenish yellow at the base before ripening. Such fruit has been termed *nigrescens*. A relatively uncommon type is green before ripening and is called *virescens*. The latter changes at maturity to a light reddish orange, although the apex of the external fruit remains greenish (Plate VIB). The frequency of the *virescens* type was found to be 50 in 10,000 bunches in a grove area in Nigeria and 72 in 10,000 in Angola (Hartley, 1988), but Rajanaidu (1986a) found 6% *virescens* in Cameroon.

The colour of the ordinary *nigrescens* fruit varies to an appreciable extent on ripening. This colour difference in ripening is recognised by some of the peoples in West Africa, where different vernacular names have been allotted to them. The terms *rubro-nigrescens* and *rutilo-nigrescens* were proposed by Purvis (1957). However, it is not always possible to assign fruit with any certainty to these subtypes, and fruit of intermediate appearance are common.

The *albescens* fruit, characterised by a very low carotene level in the mesocarp, is extremely rare. It was first noted in Ghana, under the name *abefita*, but was later named *albescens* by Beccari (1914a). It has

subsequently been found in Congo, Angola, Nigeria, the Ivory Coast and other parts of Africa. In Angola the frequency was found to be only three in 10,000. *Albescens* fruit may be of *nigrescens* or *virescens* type; in Congo the fruits were referred to as *albo-nigrescens* and *albo-virescens*. As expected, given that both forms are rare, only a very few *albo-virescens* palms have been found (Vanderweyen and Roels, 1949). The level of carotenoids in the mesocarp of non-*albescens* fruit varies (see Section 5.3.7.4), but is always much higher than in *albescens*.

Fruit form: In the internal structure of the fruit the most important differences are in the thickness of shell (Plate IIA). As shell thickness ranges from less than 1 to 8 mm it might be thought that a division of fruit into thick-shelled and thin-shelled forms would be somewhat arbitrary. However, a rare shell-less form was early noted in Africa and named *pisifera*, owing to the pea-like shell-less kernels found in fertile fruit. *Pisifera* palms always bear large quantities of female bunches. The majority of *pisiferas* are more or less female-sterile, bearing few or no fertile fruit (although the setting of a few fruit is necessary to identify them, as other infertile forms may be encountered). *Pisiferas* have been classified as:

- sterile: giving, occasionally, a few fruit, but the bunches normally rotting; vegetative development is very vigorous
- showing partial sterility: small numbers of fertile fruit per bunch; vegetative development is less vigorous than in sterile forms
- fertile: these palms are relatively rare; their value in breeding is discussed in Chapter 5.

Intermediates between these categories exist and palms tend to become less infertile as they age. In sterile fruit there is no development of the ovule, or ovular development is retarded. Abnormalities of the tissues surrounding the ovule also occur (Henry and Gascon, 1950). Sterility sometimes occurs in *tenera* and has been reported in *dura*.

Apart from the discovery of the *pisifera* it was also noted that in the majority of the thinner shelled fruit there was a distinct ring of fibres embedded in the mesocarp but near to and encircling the nut. This can be clearly seen when the fruit is cross-sectioned. In 1935 Smith recorded that 'the present dividing line between thick and thin-shelled forms is that the fruit of the latter contain the mesocarp fibre ring and the nuts can be readily cracked'. Subsequent genetic studies have shown that the thin-shelled form with a fibre ring, the *tenera*, is a hybrid between the shell-less *pisifera* and the common thick-shelled *dura* form which has no fibre

ring (Beirnaert and Vanderweyen, 1941) (see Section 5.3.3.1 for a discussion of the inheritance of shell thickness).

The term *macrocarpa* has been used for *dura* palms with shell thickness of 6–8 mm, but the term has largely gone out of use as it has no genetic significance. However, in many parts of West Africa (e.g. Sierra Leone and western Nigeria) fruit that could be described as *macrocarpa* form a large proportion of the crop. In a grove survey in eastern Nigeria 27% of the *dura* palms were classed as *macrocarpa*, and there are undoubtedly even higher proportions elsewhere (Hartley, 1988).

The mesocarp of all fruit contains fibres which run longitudinally through the oil-bearing tissue. This fibrous material usually constitutes about 16% of the mesocarp weight but may vary from 11 to 21%. The oil content of the mesocarp of ripe fruit varies from under 40% to over 60% (see Section 5.3.3.2). The fibre ring in *tenera* fruit is dark in colour; dark fibres may also be distributed in other parts of the mesocarp, although they are usually in the central section. Light-coloured fibres are distributed regularly throughout the mesocarp.

2.2.2.7 The fruit bunch

The female inflorescence at anthesis is in the axil of the 17th to 20th leaf from the central spear. Development to ripeness takes between 4.5 and 6 months, and by the time the bunch is ripe it is subtended by about the 30th to 32nd leaf (Plate ID). The bunch leans out from its subtending leaf on to a leaf in a lower whorl, so it is not the leaf subtending the bunch that supports it. The fruit develop steadily in size and weight from anthesis until 100 days or more after anthesis. The kernel is at first liquid, then gelatinous, and solidifies at about 100 days after anthesis; the embryo matures by 70–80 days, and the shell becomes hard and lignified by about 120 days. Oil formation in the kernel commences at about 70 days and is probably complete by about 120 days. Mesocarp oil synthesis starts at about 120 days, and continues until the fruit detaches from the bunch (see Chapter 13).

The ripe bunch is ovoid and may reach 50 cm or more in length and 35 cm in breadth (Plate IIB). The bunch consists of the bunch and spikelet stalks and spines, outer and inner fruit, the latter somewhat flattened and less pigmented, parthenocarpic (seedless) fruit which have developed even though fertilisation has not taken place, and undeveloped, non-oil-bearing unfertilised flowers (Plate 2.8). In parthenocarpic fruit



Plate 2.8 A bunch from a *Deli dura* palm.

endosperm and embryo are absent; the centre consists of a solid core of shell in *dura* fruit, but this core is absent in parthenocarpic *tenera* fruit. A high proportion of parthenocarpic fruit can be induced by spraying inflorescences at anthesis with an auxin such as naphthylene acetic acid or 2,4-D, but unless spraying is repeated regularly, such bunches fail to ripen (Thomas *et al.*, 1973). Parthenocarpy, usually followed by bunch failure, may also be induced accidentally by various herbicides (Wan, 1987; Khairudin and Teoh, 1988).

Bunch weight increases with palm age, with means of less than 5 kg in 3-year-old palms, to over 25 kg at 15 years (Corley and Gray, 1976b); individual bunches weighing up to 100 kg have been recorded. Bunch number produced per palm per year declines with age, so that, after reaching a peak at 6–10 years, yield remains more or less constant for many years, despite steadily increasing mean bunch weight.

Between 30 and 60% of flowers normally develop into fruit, depending on the efficiency of pollination, with a fruit-to-bunch ratio of 60–70% by weight. The relationship between fruit set (percentage of flowers that develop into fruit) and bunch weight is discussed further in Section 4.4.7.1. Well-set bunches carry from 500 to 4000 fruit, depending on bunch size; a mean of about 1500–2000 is usual in 10–15-year-old palms.

An understanding of bunch ripening is important if harvesting is to be done correctly. The first observable change is in fruit colour, with the mesocarp turning orange as carotenoids are synthesised, simultaneously with oil synthesis. Fruits then start to detach, from the

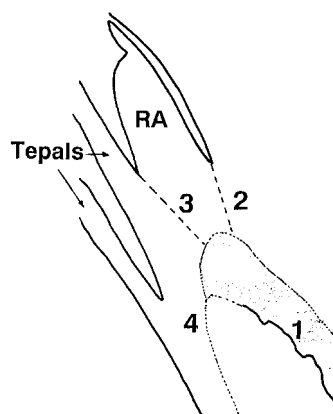


Fig. 2.8 Diagram of the abscission zone, with abscission in progress. RA: rudimentary androecium, the ring of undeveloped stamen primordia; 1: translucent area above position 1, in which separation has already occurred; 2: normal point of separation, with rudimentary androecium attached to spikelet; 3, 4: possible alternative sites of separation. [From Henderson, 1998; enlarged representation of part of Plate 2.9.]

apex downwards. Fruit abscission has been described in detail by Henderson and Osborne (1990; also Osborne *et al.*, 1992; Henderson, 1998; Henderson *et al.*, 2001). The abscission layer, at the base of the fruit, consists of two zones, a central and a peripheral (Fig. 2.8, Plate 2.9); the peripheral zone coincides with the ring of rudimentary stamen primordia (Section 2.2.3.2), and in mantled fruit, where the stamen primordia have developed into supplementary carpels, separation at this position does not occur. Abscission occurs first in the central zone: separation of the cells follows the highly localised induction of a cell wall-degrading enzyme (polygalacturonase) within the abscission layer. Once cell separation is complete in the central zone, separation also takes place in the peripheral zone, and external fruit fall from the bunch; loose fruit scattered on the ground are a signal to the harvester that the bunch is ripe. Inner fruit may remain held in place by spikelets and bracts, even though they are no longer attached, and may scatter explosively during harvest, when the cut bunch falls to the ground. Harvesting is discussed in more detail in Chapter 10.

2.3 THE AMERICAN OIL PALM, *ELAEIS OLEIFERA* (HBK) CORTES

The American oil palm (Plate VIA) has been given several different names by taxonomists in the past

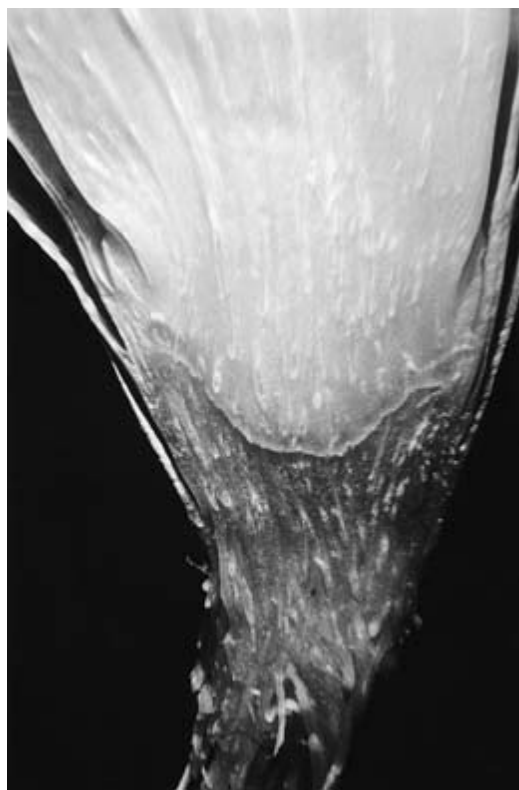


Plate 2.9 Longitudinal section through the base of a ripe fruit. Separation (abscission) starts in the central part (position 1) of the abscission zone. (From Henderson and Osborne, 1990.)

(e.g. *Elaeis melanococca* and *Corozo oleifera*; see Hartley, 1988, p. 85, for more detail), but it is now agreed that the correct name is *Elaeis oleifera* (Wessels-Boer, 1965).

2.3.1 Distribution

Elaeis oleifera is found in the tropical countries of South and Central America and has been described or collected from Brazil, Colombia, Venezuela, Panama, Costa Rica, Nicaragua, Honduras, French Guiana and Surinam (de Blank, 1952; Ferrand, 1960; Meunier, 1975; Rajanaidu, 1986b). In Colombia, it is found in depressions between rolling areas of pasture land and in damp or even swampy situations near or on the banks of rivers (Plate 2.10). In these situations it can be found in pure and dense stands, but in pasture land or in some riverbank habitats it is also found dispersed or in small groups. On the Magdalena River there are some farms where kernel oil is extracted or the fruit is fed to pigs and where palms are even selected, on

bunch production and quality, for further planting (Hartley, 1988). In Nicaragua it covers large areas on the banks of the San Juan and Escondido rivers. It tolerates both swampy and shady conditions, although under shade very few bunches are produced, while in low-lying terrain the palms on slightly raised areas are healthier. In Costa Rica, some specimens are to be found on sloping or even steep pastures, but except in tracts of unoccupied riverside semi-swamp, or in the few situations where use is being made of the bunches for oil extraction or pig feeding, the population is declining. Cattle farmers consider the palm to be an encumbrance, because it is too short to give useful shade (Hartley, 1988).

In Brazil the palm is most common in the central region of Amazonas above Manaus, and here it is distinguished by its large fruit. In Surinam there are dense stands on poor, sandy soil, and the palms are of small size. As land becomes more extensively utilised for organised agriculture, so the population of *E. oleifera* will decline; a wide gene pool has already been collected (see Section 5.1.7.3) and this should be preserved.

2.3.2 Morphology

A feature of the palm that distinguishes it from *E. guineensis* is its much shorter, and often procumbent, trunk (Plate 2.11). Annual height increment may be only 5–10 cm, less than one-fifth of that of *E. guineensis*. An erect habit may be maintained for at least 15 years (Hartley, 1988), but thereafter a procumbent habit is generally assumed. The crown remains in an erect position, with the distal 1.5–2 m of trunk being erect. Trunks lying on the soil for a distance of over 7.6 m have been measured (Hartley, 1988), but in certain areas, perhaps depending on soil type, the trunk may remain erect. In a collection of *E. oleifera* in Congo, some palms remained erect over 40 years after planting. In these palms, the bunches were no more than 3 m above ground level (N. Luyindula, pers. comm., 2000), indicating the very slow height increase of *E. oleifera*.

The root development of the palm is similar to that of *E. guineensis*, but roots which may grow to 1 m in length are formed along the whole length of the procumbent trunk. Arnaud and Rabechault (1972) suggested that anatomical differences, namely greater lignification of the hypodermis and cortical parenchyma, fewer lacunae and the presence of tannins in the cells of the endoderm and phloem, might account for resistance to certain diseases (see Chapter 12).

The leaf of *E. oleifera* also readily distinguishes it from *E. guineensis*. All of the leaflets lie in one plane and



Plate 2.10 A natural stand of *Elaeis oleifera* in the Sinu Valley area of Cordoba Province, Colombia.



Plate 2.11 Two *Elaeis oleifera* palms in the Sinu Valley, Colombia. Note the coiling, recumbent trunks.

have no basal swellings, and the spines on the petiole are short and thick. In good specimens the leaflets are larger than those of *E. guineensis*, being up to 1.9 m long and 12 cm wide (Vallejo and Cassalet, 1975). There are usually more than 100 pairs. After the leaves have been pruned, the leaf bases persist for only a short period.

The male inflorescence differs little from that of *E. guineensis*. The spikelets, of which there are between 100 and 200, varying in length from 5 to 15 cm, are pressed together until they burst through the spathe just before anthesis. The male flower is somewhat smaller with shorter anthers; the rudimentary gynoecium is more developed and has three marked stigmatic ridges.

The spathe of the female inflorescence is more persistent than in *E. guineensis*, so that even ripe bunches are still partially covered by fibrous material. The spikelets end in a short, blunt spine. The flowers are sunk in the body of the spikelet, and are not subtended by a long bract as in the case of *E. guineensis*; thus, the bunch of *E. oleifera* contains no long spines. The period of anthesis in the female inflorescence is much more erratic than in *E. guineensis* and may last for 3 or 4 weeks, or have two peaks, while other palms complete anthesis in 3 or 4 days (Rao and Chang, 1982). Palms with a long anthesis duration show uneven ripening.

The bunches are round and wide at their centre with a tendency to be pointed at the top, giving a distinctly conical appearance. They usually weigh between 8 and 12 kg but occasionally reach 30 kg. The large number of small fruit, of which the normal ones alone may number more than 5000, have been recorded in Colombia as weighing between 1.7 and 5.0 g. In Brazil, fruit weights appear greater, ranging from 5 to 13 g (Ooi *et al.*, 1981). Parthenocarpic fruit are often numerous, and may constitute up to 90% of the total. There are two types: those with a small nut with a liquid-filled cavity and smaller fruit with only a lignified central core. The mesocarp layer is thin and usually constitutes 29–42% of normal fruit, but over 80% in parthenocarpic fruit. In a survey in four regions of Colombia the mean ratio of oil to fresh mesocarp was found to vary with locality from 17 to 23% in normal fruit, with lower oil percentages in parthenocarpic fruit (Vallejo and Cassalet, 1975).

Shell thickness varied from 1 to 3 mm and the shell formed between 43 and 53% of the fruit. There was between 13 and 22% of kernel; nuts with two kernels were fairly frequent and those with three kernels occasional. In Brazil, the fruit contained rather more mesocarp (35–60%) and less shell (28–47%), with 10–24% kernel (Ooi *et al.*, 1981). The oil-to-bunch ratio may be no more than 4% (Oboh, 1993).

Fruit-to-bunch ratios are often low; the mean percentage normal fruit to bunch in the Colombian survey varied from 28 to 46%, with mean parthenocarpic fruit-to-bunch ratio varying from 9 to 23%. Within-region variations were very great and some bunches were found with normal fruit-to-bunch ratios as low as 9% or as high as 64%. Normal plus parthenocarpic fruit usually constitute less than 60% of the bunch, and as parthenocarpic fruit form such a high percentage of all fruit, kernel production is considerably lower than indicated by normal fruit analysis and total fruit-to-bunch percentages. The proportion of normal fertile fruit can be substantially raised by controlled pollination of the inflorescences (Tam, 1981).

There is some variation in fruit colour. About 90% of palms have orange fruit at maturity, these having developed from immature fruit which were at first yellowish green, then ivory coloured at the base and orange above. A less common type of fruit is yellow at maturity and has developed from immature fruit at first bright green, then turning olive green and pale yellow (Hurtado and Ramos Nunez, 1970). The small palms in Surinam are reported to have green immature fruit turning orange to red (Meunier, 1975). There is no evidence that fruit forms comparable to *dura*, *tenera* and *pisifera* exist in populations of *E. oleifera* (but see Section 2.4). Compared with *E. guineensis* the oil has a higher oleic acid content and iodine value (see Section 5.3.7.1). The carotene content is higher than that of the Deli palm but may be no higher than that of many *E. guineensis* palms in Africa.

2.3.3 Uses

Apart from its domestic use in many areas as a cooking oil, the mesocarp oil has been used locally for soap making and as a lamp oil, while the kernel oil has been sold as a hair oil.

The main possible value of the palm is for hybridisation with *E. guineensis*, on account of the slow growth in height of *E. oleifera*, and through the characteristics of its mesocarp oil. Interest in *E. oleifera* increased following the recognition of its resistance of fatal yellowing in Colombia (see Chapter 12), a discovery

that led to the establishment of the first commercial plantation of the hybrid of the two species of *Elaeis* (Turner, 1981).

2.4 THE *ELAeis GUINEENSIS* × *ELAeis OLEIFERA* HYBRID

The two species have frequently been hybridised on an experimental scale, and the significance of the cross in selection and breeding is discussed in Chapter 5. The hybrid has leaves that are considerably larger than those of either parent, but retain the leaflet arrangement of *E. oleifera*. The characteristics of the latter palm as regards height increment, falling leaf bases, persistent spathes, parthenocarpy, and fruit shape and colour are also retained in the hybrid. As both the flower-subtending bracts on the spikelets and the spines at the spikelet ends are only slightly longer than in *E. oleifera*, hybrid bunches closely resemble those of that species. Andromorphism (Section 2.2.2.4) is not uncommon in young palms.

Hartley (1988) quoted unpublished data from Tan Y.P. showing higher leaf production in *E. guineensis* than in the hybrid, but Hardon (1969) found little difference. The number of leaflets in the hybrid is intermediate between the parent species, but the hybrid has larger leaflets than *E. guineensis* and a greater leaf area than either parent (Hardon, 1969).

Pollen grains of *E. oleifera* are mainly elliptical, not triangular like those of *E. guineensis*. Hybrid pollen is intermediate in shape and varies greatly in size. Abnormal cell divisions are frequent during pollen grain formation, and pollen viability and germination percentage are low (Hardon and Tan, 1969). Partly as a result of this, fruit set in the hybrids is usually poor. A second probable cause of poor fruit set is that the hybrid inflorescences appear to be less attractive to *Elaeidobius kamerunicus*, the pollinating weevil (Tan, 1985). Reasonable fruit set is sometimes observed in trials with hybrids, but it appears that this may be brought about by *E. guineensis* pollen from neighbouring plots of that species; Sharma and Tan (1990) noticed a decrease in fruit set in a hybrid block when the *E. guineensis* field surrounding it was felled for replanting.

The internal fruit characters of the hybrid depend on the fruit form (*dura*, *tenera* or *pisifera*) of the *E. guineensis* parent. Although there appears to be no variation in fruit form in *E. oleifera*, the shell-thickness gene does function in the hybrid. Crosses between *E. oleifera* and *pisifera* have thin shells, but lack the fibre ring seen in *E. guineensis tenera*s. In normal fruit

from crosses with *dura*, mesocarp-to-fruit varies from under 40 to over 50%, but fruit from *tenera* and *pisifera* crosses has given mesocarp percentages of 58–74% (Obasola, 1973a; Vallejo and Cassalett, 1975). With parthenocarpic fruit, mesocarp percentage depends on the degree of parthenocarpy. In a Malaysian trial large parthenocarpic fruit had a mean of 75% mesocarp with 25% shell, while the small type had 89% mesocarp, the lignified core only accounting for 11% of the fruit. Oil-to-mesocarp is intermediate between that of the parent species, and the distribution of fatty acids also appears to be intermediate (Hardon, 1969) (see Section 5.3.7.1).

Hybrid bunches may ripen normally, but sometimes show great irregularities; the latter may be caused by insufficient set of normal fruits, in which case higher fruit on the spikelets often fall out at the start of ripening, while in other cases a poor set may lead to full or partial bunch failure 1–3 months after anthesis. Normal fruit turn from black to yellow in the fifth month, then become orange–yellow and finally orange–red. Genty and Celis (1997) noted that fruit detachment and build-up of free fatty acids were slow compared with *E. guineensis*.

Chapter 3

The Climate and Soils of the Oil Palm-growing Regions

3.1 GENERAL

Soil and climate are the basic resources for growing crops. It is possible to amend either in some ways, such as the chemical composition of soil with fertilisers, or the rainfall regime with irrigation or rain-saving systems, but such amendments can be expensive. Other components of these resources, such as the physical nature of soils, or the temperature regime in climate, are virtually impossible to alter on a large scale. The nature of both soils and climate needs careful investigation before land is acquired prior to planting oil palms, or any other crop. Despite this there are well-known stories of agricultural developments being started without proper climatic records or soil surveys, with consequent huge losses. Even now it appears that areas of land are sometimes bought and palms are planted before a proper soil survey has been done, with predictable consequences. It is important that these issues are fully understood by anyone professionally involved with oil palms.

In this chapter the effects of climate are defined, including a specification of the best climates for the oil palm. However, the oil palm has been profitably cultivated in many areas that appear suboptimal. The reasons are, first, that the plant is adapted to a climatic regime of summer rainfall and winter drought. Hence, even if the fresh fruit bunch (FFB) yield is decreased by a 3-month-long dry season, the general health of the palm suffers little (see Section 4.3.3). The bud continues to grow and spear leaves to emerge, but they usually do not expand until the next rainy period. Secondly, the oil palm is so productive that its cultivation has been profitable even in unfavourable circumstances if costs are low, or there is a good internal market for the product. Thirdly, there are few profitable alternative treecrops. The effective geographical and altitudinal limits seem to be widening, as the economic case for growing oil palms becomes more widely appreciated. There are now developing plantings, or at least strong interest, in India, Bangladesh (Hassan, 1985), China, Ethiopia and other countries outside the usual oil palm regions.

3.2 CLIMATE

3.2.1 Temperature

The oil palm demands high temperature, as it is an equatorial crop. It is, however, difficult to separate the effect of maximum and minimum temperature. The best mean temperature range seems to be 24–28°C, although palms at high elevation, or at the geographical limit of about 15°N may be growing with mean minimum temperatures of less than 20°C for part of the year (Table 3.1).

Controlled experiments at constant temperatures have shown that growth of seedlings was best at 25°C, where growth was seven times, and at 20°C three times, as rapid as at 17.5°C (Henry, 1958). At 15°C no growth took place. Ferwerda (1977) measured growth in a phytotron, with light and dark temperatures 10°C different, both being altered between treatments by 5°C steps. The best growth was at 32/22, mean 27°C. The next level, with a mean temperature of 22°C, gave only slightly slower growth, but at a mean temperature of 17°C it was only about half of the best, and very little growth occurred at a mean temperature of 12°C (17/7).

Goh (2000) listed the consequences of low temperature, which may be found at the geographical limits to growth. These are increased abortion, and slow vegetative growth and bunch ripening. It is likely that the palm grows best where the seasonal temperature change is least, but up to the limit of the 6°C seasonal variation found in commercial growing areas, there appears to be little effect on the palm (Goh, 2000) (Table 3.1). Goh (2000) suggested that the lowest mean temperature supporting oil palms at high altitude may be around 20°C. However, Tela in Honduras has 4 months with mean minimum temperatures around 18°C. This climate produces a strongly seasonal yield pattern, and nearly 90% of the crop is harvested between June and December, owing to abortion and lower sex ratio in the winter (Hartley, 1988). A useful presentation is that of Olivin (1986), which shows how the maximum and minimum temperatures are distributed by month at various sites (Table 3.2);

Table 3.1 Temperatures (°C) in some centres of oil palm cultivation: mean, mean maximum and mean minimum

Centre		Lat. and long.	No. of years		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Av.	
Asia																		
Malaysia	Telok Anson	4°2′ N, 101°1′ E	20	Mean	27.6	28.0	28.4	28.7	28.7	28.5	28.1	28.0	28.0	27.9	27.7	27.4	28.1	
				M. max.	32.6	33.1	33.5	33.7	33.6	33.4	33.1	32.9	32.7	32.4	32.1	32.0	32.9	
				M. min.	22.6	22.9	23.2	23.6	23.8	23.5	23.1	23.1	23.2	23.3	23.2	22.8	23.3	
	Layang-Layang, Johore	1°15′ N, 103°30′ E	18	Mean	25.6	26.0	26.6	27.1	27.3	27.0	26.6	26.7	26.7	26.9	26.6	25.9	26.6	
				M. max.	30.6	31.4	32.5	32.7	32.7	32.4	31.7	31.8	31.9	32.1	31.5	30.3	31.8	
				M. min.	20.5	20.6	20.6	21.4	21.8	21.6	21.6	21.5	21.4	21.7	21.6	21.4	21.3	
	Sumatra	Medan	3°35′ N, 98°41′ E	10	Mean	25.4	26.0	26.4	26.5	26.8	26.5	26.4	26.1	25.9	25.7	25.4	25.3	26.0
					M. max.	29.9	31.3	31.5	31.6	31.7	31.4	31.8	31.2	30.9	30.1	29.7	29.6	30.9
					M. min.	22.2	22.1	22.5	22.8	23.2	22.7	22.4	22.3	22.4	22.6	22.5	22.3	22.5
Africa																		
Sierra Leone	Njala	8°6′ N, 12°6′ W	32	Mean	26.1	27.4	27.9	27.2	27.3	26.1	25.2	24.6	25.6	26.2	26.3	26.2	26.4	
				M. max.	32.3	33.0	33.3	32.8	32.6	30.7	28.9	28.2	29.5	31.0	31.3	31.4	31.5	
				M. min.	19.8	20.7	21.3	21.8	21.8	21.5	21.4	21.5	21.6	21.3	21.3	20.5	21.2	
Ivory Coast	La Mé	5°3′ N, 3°5′ W	19	Mean	26.1	27.3	27.5	27.4	26.8	25.6	24.6	24.3	25.0	25.9	26.1	25.8	26.0	
				M. max.	31.2	32.2	32.2	32.1	30.9	28.8	27.8	27.2	28.3	29.7	30.5	30.3	30.0	
				M. min.	20.9	22.4	22.7	22.7	22.6	22.4	21.4	21.4	21.8	22.0	21.6	21.2	21.9	
Nigeria	NIFOR, Benin	6°30′ N, 5°40′ E	12	Mean	26.3	27.5	27.4	26.9	26.5	25.6	24.6	24.3	25.0	25.6	26.2	25.8	26.0	
				M. max.	30.9	32.7	32.4	31.5	30.9	29.4	27.6	27.4	28.3	29.6	30.7	31.2	30.2	
				M. min.	21.6	22.3	22.4	22.2	22.0	21.7	21.5	21.3	21.8	21.6	21.6	21.4	21.8	
Cameroon	Lobé	4°30′ N, 9°10′ E	15	Mean	26.7	27.4	27.4	27.1	26.8	26.0	24.9	24.5	25.2	25.8	26.6	26.5	26.2	
				M. max.	31.4	32.1	31.8	31.4	31.0	29.6	27.8	26.9	28.2	29.4	30.7	30.9	30.1	
				M. min.	22.0	22.7	22.9	22.8	22.6	22.4	22.0	22.1	22.1	22.1	22.5	22.0	22.3	
Congo	Yangambi	0°49′ N, 24°29′ E	10	Mean	24.1	24.1	24.3	24.4	24.1	23.6	23.1	23.0	23.2	23.3	23.5	23.4	23.7	
				M. max.	30.2	30.8	30.6	30.3	30.1	29.5	28.5	28.4	29.2	29.1	29.3	29.0	29.6	
				M. min.	19.6	19.4	19.9	20.3	20.0	19.8	19.3	19.5	19.4	19.5	19.7	19.5	19.7	

Centre		Lat. and long.	No. of years		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Av.
America																	
Brazil	Iguape, Bahia	12°31' S, 39° W	8	Mean	25.5	26.8	26.6	26.4	25.2	23.6	22.5	21.9	22.1	23.7	24.3	25.5	24.5
				M. max.	30.6	32.3	31.9	31.1	29.2	27.1	26.2	25.8	26.4	28.6	29.1	31.0	29.1
				M. min.	20.3	21.4	21.2	21.6	21.2	20.1	18.7	17.9	17.7	18.8	19.5	20.4	19.9
	Paricatuba, Belém, Pará	1°16' S, 48°8' W	17	Mean	26.4	26.3	26.5	26.6	26.7	26.3	26.0	26.1	26.0	26.1	26.1	26.7	26.3
				M. max.	31.3	31.0	31.1	31.4	31.5	31.4	31.1	31.4	31.3	31.5	31.4	31.6	31.3
				M. min.	21.4	21.5	21.8	21.9	21.8	21.2	20.8	20.8	20.7	20.7	20.7	21.8	21.3
	Aracataca	10°35' N, 74°9' W	13	Mean	27.3	27.4	27.5	28.9	28.4	27.8	28.0	27.9	28.1	27.5	27.5	27.8	27.8
				M. max.	33.3	33.2	32.8	34.6	33.8	33.0	33.7	33.9	33.9	33.7	33.0	34.0	33.5
				M. min.	21.4	21.7	22.3	23.2	22.9	22.7	22.4	22.3	22.4	22.2	22.1	21.7	22.3
	Barrancabermeja	7°4' N, 73°52' W	23	Mean	29.3	29.6	29.7	29.4	28.9	28.9	29.2	28.8	28.7	28.7	28.6	29.1	29.0
				M. max.	33.1	33.7	33.6	32.9	32.5	32.7	33.3	33.1	32.5	31.9	32.1	32.9	32.9
				M. min.	25.5	25.6	25.8	25.8	25.3	25.2	25.0	24.6	24.8	24.5	25.1	25.3	25.2
	Rio Mira, Tumaco	1°30' N, 78°40' W	5	Mean	26.7	27.6	28.2	28.2	27.8	28.4	28.4	28.1	28.2	27.7	27.9	26.6	27.8
				M. max.	28.7	29.7	30.6	30.6	30.2	30.7	30.9	30.4	30.5	30.0	30.5	28.5	30.1
				M. min.	24.7	25.4	25.7	25.8	25.7	26.0	25.9	25.6	25.8	25.4	25.3	24.6	25.5
Ecuador	La Concordia	0°05' N, 79°20' W	8	Mean	25.2	25.2	25.5	25.8	25.1	24.3	23.6	23.5	23.8	23.6	23.3	24.1	24.4
				M. max.	29.0	29.5	30.0	30.2	29.0	27.8	27.5	27.5	27.6	27.5	27.2	27.9	28.4
				M. min.	21.3	20.9	20.9	21.3	21.2	20.5	19.6	19.4	20.0	19.7	19.3	20.3	20.4
Honduras	Tela	15°43' N, 87°29' W	10	Mean	23.0	23.5	24.3	25.6	26.0	26.3	26.2	26.6	26.1	25.3	23.6	23.4	25.0
				M. max.	27.8	28.4	29.6	31.5	31.2	31.6	31.8	32.1	32.2	30.1	28.4	28.6	30.3
				M. min.	18.1	18.7	18.9	19.6	20.8	20.8	20.6	21.1	21.0	20.4	18.7	18.1	19.7
Costa Rica	Quepos	9°26' N, 84°9' W	32	Mean	23.6	22.9	23.6	25.6	26.8	27.1	27.2	27.0	26.5	26.6	23.8	23.2	25.3
				M. max.	28.5	27.8	28.5	31.1	31.9	32.0	32.0	31.7	31.2	31.1	28.7	27.8	30.2
				M. min.	18.8	18.0	18.7	20.2	21.7	22.2	22.5	22.3	21.9	22.2	18.9	18.7	20.5

After Hartley (1988).

Table 3.2 Classification of monthly maximum and minimum temperatures (°C), by numbers of months of occurrence, for a number of oil palm-growing stations and plantations, together with annual means, mean maxima and mean minima

		Temperature (°C)																			Annual means		
		17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	Max.	Min.	Mean
		No. of months																					
Colombia																							
San Alberto	Max.																	2	5	5	33.9		28.1
	Min.						1	11														22.3	
Ivory Coast																							
La Mé	Max.												2	2	1	3		1	3		30.0		26.0
	Min.						6	6														21.9	
Peru																							
Tocache	Max.														2	10					30.2		25.2
	Min.				4	7	1															20.2	
Ecuador																							
Quininde	Max.													8	2	2					29.1		25.2
	Min.					5	6	1														21.2	
Vanuatu																							
Santo	Max.										1	4	2	3	2						27.5		24.6
	Min.					2	6	4														21.6	
Madagascar																							
Tamatave	Max.									2	2	0	2	2	4						27.6		23.8
	Min.		4	1	1	1	1	4														19.9	

After Olivin (1986).

Tamatave in Madagascar has a particularly low minimum in 4 months.

Temperatures are always more extreme at the centre of land masses. The Congo has a low night temperature; at Yangambi the mean minimum for all months is between 19.3 and 20.3°C. Hartley (1988) suggested that, as this is the only significant difference from the climate in Malaysia, it is the cause of the relatively low yields in Zaire. This is supported by the low-temperature limits at or below 18°C in West Africa, which may have a similar effect (Fig. 3.1). Hartley (1988) reported that at 500 m elevation in Sumatra, palms came into bearing at least a year later than palms growing at the usual altitudes. The decrease in temperature with altitude is important, as there are moves towards planting commercial palms in some high locations, such as Ethiopia. Palms are being bred for high altitude and low temperature (Chapman *et al.*, 2001), although as yet there seems to be little demonstrable progress.

3.2.2 Rainfall, evaporation and water balance

3.2.2.1 Evapotranspiration

Water supply is a difficult factor to define in detail because it contains several time-dependent variables,

and there are wide possibilities of intra-annual and interannual variation. The most important intra-annual variations are usually expressed as the rainfall and the potential evapotranspiration per month (Tables 3.3, 3.4). Rainfall through tree canopies can be divided into direct rainfall to the soil, stem flow down the trunk and intercepted water, the last being water that is held by and eventually evaporated directly from leaves (Squire, 1984c). The shape of the palm canopy causes the local rainfall under it to vary considerably from the trunk out to the circumference, with a concentration immediately around the trunk and at the outer circumference of the leaves (Tinker, 1959). These differences may affect local leaching or the beginnings of erosion incidents, but there is no reason to make such distinctions in the overall water balance. Information is still inadequate, but some time between the ages of 4 and 10 years the root system fully occupies the topsoil of the field, and from then on any incident water will be available so long as it remains within the rooting zone (see Section 11.2.1.1). The incoming rainfall (plus irrigation if applied) is divided into soil water increase or decrease, surface runoff (output to downslope or input from upslope), deep percolation to the water table, and evaporation from the soil surface and the leaves of the palms and all other vegetation. In total, the last is called

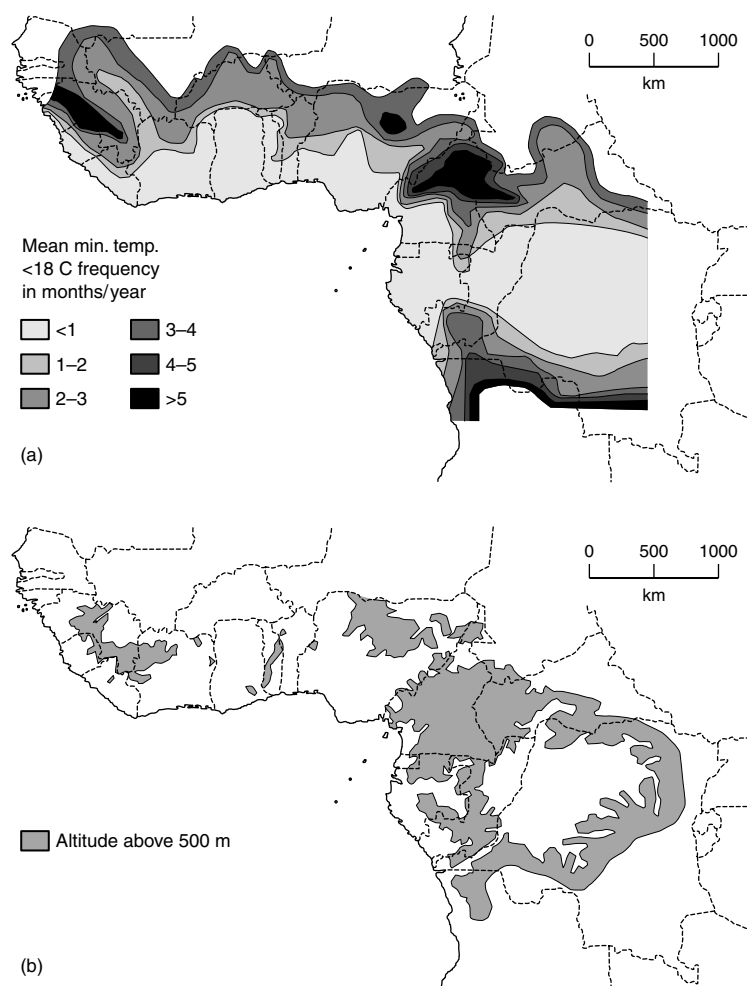


Fig. 3.1 Distribution of frequency of occurrence (months per year) of minimum temperatures below 18°C in West and Central Africa compared with land at altitudes above 500 m. (After Quencez, 1996.)

the evapotranspiration (see Equation 3.1) (Lim *et al.*, 1994).

There is a great deal of confusion over terminology for evapotranspiration in the oil palm literature, and we have clarified this by defining major terms. *Potential evapotranspiration* (Eo) is the amount of water, expressed in millimetres, that would be evaporated into the air during a specified period from a hypothetical standard crop surface (grass, 0.15 m tall, with complete ground cover) liberally supplied with water. This depends on the input of energy to supply the latent heat of evaporation. It is determined by climatic factors (temperature, incident radiant energy, advective energy brought in by the wind, and vapour pressure deficit of the air) and can be estimated from the Penman–Monteith equation (Monteith, 1981; Allen *et al.*, 1998). Evaporation from an open

water surface, as in an evaporation pan, gives *pan evaporation*, which approximates to Eo in practice. However, the figures obtained depend on the design of the pan, and often differ to some degree from Penman–Monteith estimates in the same environment.

Crop potential evapotranspiration (Ec) is the amount of water transpired by a specific crop liberally supplied with water. This can be measured under conditions where water is in ample supply to plants, such as in a lysimeter with irrigation, where the total water balance can be determined. Ec will depend on the characteristics of the crop surface, and may not be the same as Eo: the ratio between Ec and Eo is known as the ‘crop factor’. For example, Henson (1995a) found that the actual daily evapotranspiration from palms under conditions when water was not limiting ranged from 0.8 to 1.2 of Eo

Table 3.3 Average rainfall (mm) at some centres of oil palm cultivation

Centre		Lat. and long.	No. of years	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	
Asia																	
Malaysia (West)	Telok Anson	4°2' N, 101°1' E	34	185	191	217	242	171	96	124	122	79	284	289	246	2,348	Coastal plain
	Paya Lang	2°35' N, 102°40' E	20	106	138	146	136	145	95	117	90	142	155	217	191	1,678	Inland S
	Layang-Layang	1°15' N, 103°30' E	18	135	150	158	230	167	149	164	169	170	210	230	248	2,180	Inland S
	Jerangau	4°59' N, 103°9' E	25	297	168	132	144	196	206	214	256	287	343	569	839	3,651	E coast state
Malaysia (Sabah)	Mostyn	5°N, 118°5' E	30	195	119	137	198	222	209	165	181	209	225	187	192	2,239	E coast
	Beluran	4°3' N, 117°30' E	27	520	354	265	125	190	249	206	234	255	241	230	408	3,278	NE coast
Indonesia (Sumatra)	Medan	3°35' N, 98°41' E	58	114	91	104	132	175	132	135	178	211	259	246	229	2,487	E coast 20 km
	Tindjowan	3°6' N, 99°29' E	26	156	109	141	154	140	111	109	170	202	244	205	171	1,912	E coast 22 km
	Marihat Baris	2°58' N, 99°6' E	21	311	223	287	305	296	214	201	277	358	452	411	292	3,627	60 km inland
Africa																	
Sierra Leone	Njala	8°6' N, 12°6' E	39	12	22	79	127	251	364	418	517	437	338	180	38	2,822	Inland
Ivory Coast	La Mé	5°3' N, 3°5' W	40	25	64	125	139	246	468	197	41	97	169	149	70	1,790	
Ghana	Aiyinasi	5° N, 2°20' W	10	37	71	140	191	378	751	293	64	116	246	129	98	2,511	SW
Benin	Pobé	6°6' N, 2°4' E	40	14	38	96	136	189	190	114	50	132	159	35	9	1,162	
Nigeria	NIFOR, Benin	6°30' N, 5°40' E	33	14	29	98	161	192	254	350	221	306	223	58	10	1,916	Mid-West
	Umudike	5°29' N, 7°33' E	36	22	51	113	204	267	273	312	253	310	262	84	18	2,168	SE
	Abak	5°5' N, 7°40' E	18	29	47	131	196	237	310	357	317	384	300	134	30	2,472	SE
Cameroon	Lobé	4°30' N, 9°10' E	27	27	72	165	199	194	345	627	820	609	302	127	21	3,508	Inland
America																	
Brazil	Paricatuba, Belém	1°16' S, 48°8' W	17	359	405	494	410	398	202	184	179	203	139	113	219	3,306	Lower Amazon
	Taparoa, Bahia	13°32' S, 39°6' W	5	118	135	305	215	183	193	131	152	86	116	123	142	1,899	Coast
Colombia	Aracataca	10°35' N, 74°9' W	13	2	8	9	52	216	178	125	182	275	344	239	31	1,661	North
	San Alberto	7°40' N, 73°30' W	17	47	55	123	295	374	228	187	213	322	405	338	117	2,704	Central
	Rio Mira, Tumaco	1°33' N, 78°41' W	15	330	364	328	388	488	432	184	169	204	185	115	167	3,354	Pacific coast
	Casanare	6°20' N, 70°30' W	7	3	62	107	340	359	313	283	272	218	273	117	27	2,374	Oriente
Ecuador	La Concordia	0°05' N, 79°20' W	15	487	474	630	579	316	214	85	56	82	58	41	166	3,188	Pacific coast
Costa Rica	Quepos	9°26' N, 84°9' W	28	57	25	39	110	340	394	420	422	436	606	312	146	3,307	Pacific coast
Honduras	San Alejo, Tela	15°40' N, 87°40' W	19	214	234	116	67	59	166	183	253	235	322	412	405	2,666	North coast

After Hartley (1988).

Table 3.4 Potential evapotranspiration (Eo) and actual evapotranspiration (Ea) measured for palms of different ages, in different sites in Africa and Malaysia

Palm age (years)	Eo	Remarks regarding Eo	Ea	Reference/location
1–3, immature with legume cover	Mean = 4.3 mm/day estimated from meteorological data		Mean = 3.3 mm/day <2.5 mm/day during dry spells	Ling (1979) Sg. Tekam, Malaysia
3–7	Range of 5.5–6.5 mm/day under drought conditions	3–3.5 mm/day during the wet monsoon with low sunshine hours 10 mm/day during extended drought conditions		Foong (1993) Sg. Tekam, Malaysia PET under irrigated conditions
7–15	Range of 6–7 mm/day under drought conditions			
>15	7–8 mm/day			
4–6	Range of 2.2–23 mm/day Mean = 7 mm/day	Extremely high demand during 5 months of exceptionally dry season	3.5 mm/day	Omoti <i>et al.</i> (1988) Nigeria. Ea by soil moisture depletion method
22–24	Range of 3.2–30 mm/day Mean = 8.9 mm/day		2.5 mm/day	

After Kee *et al.* (2000, and pers. comm.).

calculated by the Penman equation. Foong (1999) determined values of E_c for a single irrigated palm as 3.5 mm during the monsoon, but up to 10 mm during the intense droughts in the El Niño event in 1997.

Actual evapotranspiration (Ea) is from a crop without unlimited water supply. When the soil is wet, Ea is close to E_c ; as the soil dries, Ea depends on soil water availability, or more precisely, on the distribution of water potential within the root zone. Approximately, it is related to the *soil water deficit* (Sections 3.2.2.3, 4.3.3). The internal water potential of the plant becomes more negative if the soil cannot supply water to the plant at the rate required for evapotranspiration to proceed at the potential rate E_o . The plant uses various methods to prevent desiccation, the main one being closure of the stomata in the leaf surface, which reduces the transpiration rate (see Sections 4.3.3.1 and 10.3.1.1). The temperature of the leaf then rises, so that more sensible heat is lost directly to the air, rather than as latent heat of evaporation. Ea does not normally vary as much as E_o , because most of the extreme values of E_o occur during droughts, when the stomata are closed and Ea is limited (Table 3.4). This loss continues until the soil water reaches *permanent wilting point* at 1.5 MPa (15 bars) water tension, when the plant can extract water only very slowly, so that it wilts irreversibly.

Water is also evaporated directly from the soil surface, depending on the soil moisture in the top layer and the amount of radiative and advective energy reaching it. Therefore, evapotranspiration is usually stated in terms of a ground area, and covers all losses of water to the atmosphere from that area. The differences between E_o and Ea for various conditions at several sites in Asia

and Africa are given by Kee *et al.* (2000) (Table 3.4). The evapotranspiration from treecrops and arable crops will differ under identical conditions, mainly because their crop factor is altered by the different leaf cover and different architecture of their leaf canopies. Radersma and De Ridder (1996) compared water use by oil palms, cocoa, rice and maize in this way.

3.2.2.2 The water balance and soil water

The difference between the input of water as rain or irrigation, and the loss of water through actual evapotranspiration and other processes (see Equation 3.1) determines net gain or loss over a period, or the *water balance*. Some water may be lost by runoff on the surface. Runoff may occur under heavy rainfall before the field capacity has been reached, if the infiltration capacity of the soil is too small to allow it to accept the rainfall. Heavy rainfall will itself break down the surface soil structure, and so decrease the infiltration rate during the rainfall episode, so this rate cannot be assumed to be constant (see Table 11.30, Section 11.7.4.1).

If the net water balance is positive, water is stored in the soil profile up to a limiting capacity (*field capacity*), after which surplus water is lost by deep percolation through the soil. The field capacity is defined as the water left in the field soil profile after 48 h of free drainage. Smaller soil samples are measured in the laboratory, where 0.1 bar tension is applied to them and the equilibrium water content is measured. The amount of water held between this condition and the permanent wilting point is the *available water capacity* (AWC), which is

stated for a unit volume of soil as a weight or volume fraction; for a specified soil depth, or for a whole soil profile in the field it is stated as millimetres of water depth. The AWC depends on soil structure and texture, and varies widely between soils; for example, the available water in the Malaysian inland soils is only about half that of the coastal alluvial soils (Lim *et al.*, 1994).

The water held at above wilting point tension is the available water (AW). If the net balance is negative, the plant depletes the AW already stored in the soil. The total plant-available water in a soil profile is that held in all soil layers down to the lowest depth from which roots can extract water (see Section 11.2.1.1). There is no exact depth below which water is unavailable, as it depends on plant root system distribution and plant species, and also on the rate of capillary movement of water up through the profile in response to the uptake of water by roots and evapotranspiration from the soil surface. However, the rate of extraction of water by the root system can be even more important than the total amount that is theoretically available, because water has to be taken up at a rate to meet the Ea evaporative demand.

An approximate single depth for the limit of plant-available water is used for simplified work, but an accurate treatment demands a mathematical model, because of the different rates at which water at different depths is exploited (Campbell, 1991; Tinker and Nye, 2000). With oil palms this depth limit has usually been taken as 100–200 cm, which includes nearly all the fine roots (Surre, 1968; Tailliez, 1971; Tinker, 1976; Jourdan and Rey, 1996). Deeper roots can extract water from some soils (Section 11.2.1.2), but more slowly because the root density at depth is usually small, so that the stomata mostly remain closed when the plant is wholly dependent on these deep roots. This supply may be sufficient to keep the palm alive during a dry season, but not sufficient to maintain the yield level.

3.2.2.3 Water deficits

The water balance is expressed by the equation:

$$AW2 = AW1 + R + I - Ea - S - D \quad (3.1)$$

where AW1 and AW2 are the available water held in the profile down to the depth limit at the beginning and end of the measurement period, R is the rainfall, I is the irrigation, Ea is the actual evapotranspiration, S is the net surface runoff and D is the deep or lateral drainage from the profile to beyond the rooting zone. All are stated in terms of mm depth of water.

The maximum water held in a profile is the field capacity of that profile, but the field capacity per unit depth

varies with texture and structure at each level. If AW1 is the summed value for available water over the whole rooting zone when it is at field capacity, no more water can be stored, and added water runs off or drains. Conversely, if the water balance is negative, the available water is gradually removed by the roots or by surface evaporation, so that AW2 declines with time. The difference between the field capacity and the actual amount held at a given time (AW) is the *soil water deficit* (SWD) at that time. If the water balance is calculated over long periods, it will give an indication of the net deficit of supply of water compared with the demand for water over the period, but it may not indicate the real water deficit experienced by the palm during this time, for two reasons. First, some of the measured rainfall may run off during heavy storms. Secondly, if the total AW at any time exceeds the field capacity, there will be loss of water by deep drainage. In this case the soil profile may hold more than field capacity for the 2 days before the field capacity is reached and during this time some of the excess water may be transpired.

The cumulative total value of the deficit reached during a single period, such as a dry season or a year, is sometimes quoted as an indication of the severity of drought. The term *potential water deficit* (PWD) is defined as the water deficit that would develop if soil water were unlimited and Ea continued at the potential rate for the crop (Ec or Eo). This is often taken as an indication of the degree of water stress that develops over a dry season. PWD has the advantage that it can be calculated from rainfall and Ec, or Eo and a crop factor, without knowledge of Ea or AWC. It may also be possible to determine a *critical deficit* (CD), above which plant functions such as growth or yield start to be affected. This will vary with soil properties, and probably also with palm age (see Section 10.3.1.2).

The IRHO (Institut de Recherches pour les Huiles et Oléagineux) method of calculating water deficits does not fit with any of the above definitions, but it has been widely used in the oil palm industry, so requires explanation. It measures a form of PWD, but uses a very simple water balance, and assumes that the available water is between 1 and 2 mm per cm of soil depth, up to a maximum of 200 mm in deep soils. Crop potential evapotranspiration (Ec) is not measured directly, as the availability of meteorological data other than rainfall is often scarce. The simplified rules are based on the idea that the number of days with rain can indicate the total solar radiation. Eo is assumed to be 150 mm per month if there were fewer than 10 rain days, and 120 mm if there were 10 or more rain days. It is possible to use the system based on weekly or 10 day periods (e.g. Caliman and Southworth, 1998), but the principle is the same.

The assumptions on E_c and AWC are reasonable, but the calculation method is such that no deficit occurs until $AW = 0$ (i.e. all soil water in excess of the wilting point has been used). This contrasts with the standard PWD calculation, where a deficit starts to accumulate as soon as E_c exceeds rainfall. In effect, it is being assumed that the CD is 200 mm, and the IRHO deficit is a measure of the duration and intensity of the drying period during which the palm is subjected to a potential deficit greater than the CD. It is really only suitable for climates with long, intense dry seasons. (See Chapter 10 for further discussion.)

The IRHO method was originally developed to provide estimates of the suitability of new areas for oil palm, when the only weather data available were rainfall figures (Surre, 1968). It may be adequate for this purpose, but it is clearly not appropriate to be used for short-term estimates of water stress. In many oil palm publications, however, it is the only measure of water deficit given, and it is not possible to convert IRHO deficits into a standard form without further information.

Table 3.5 (Hartley, 1988) shows the relationship between annual rainfall and annual water deficit (IRHO method) at eight sites. The two quantities are negatively correlated but not closely so. Mean annual deficits were higher when calculated by the IRHO method than when they were calculated by other methods (Hartley, 1988), presumably because other calculated values cannot exceed the available water (see Section 10.3.1.2). Van der Vossen (1969a) considered that the IRHO methods overestimated the size of both the evapotranspiration and the available water, partly because they considered the depth of root extraction to be down to 200 cm.

From full water balance data from a site in Peninsular Malaysia the principles of measuring the deficit can be

seen (Table 3.6) (Kee *et al.*, 2000). These authors noted the small number of sites for which such important data are available, and have urged that more work should be done on representative sites. Given these data, the water use by the palm and the water deficit at different times of the year can be calculated, and with a suitable model the effects on yield can be found and related to the water stress (see Chapter 4).

More detailed work has been done in the Ivory Coast during a limited part of the dry season, when it could be assumed that there was no deep percolation (Rey *et al.*, 1998). In this work E_a was calculated from data of rainfall, soil water content and the water lost from the soil by evapotranspiration. The soil measurements were made with neutron moisture meters. In the late rainy season unknown amounts of deep percolation below the lower limit of measurement of 5 m made the method invalid. This work attempted to determine a practical limit to the amount of water that could be taken from the soil by the plant without serious changes in its growth and bunch yield due to water stress (CD). This critical deficit must be less than the available water at field capacity, all of which is certainly not absorbable by the palm at the E_c rate when the soil water potential is several bars. The level of stress was assessed by measurements of leaf stomatal conductance. These authors found that the CD, which they called the 'easily usable reserve', was around 70% of the AWC, as no stomatal closure occurred until 70% of AWC had been used. With $AWC = 251$ mm, the critical deficit on this soil was thus 175 mm. Water uptake continued at a reduced rate beyond the CD, and only 1.4% of AWC remained as AW in April. The primary roots in this experiment were found down to 60 cm, but secondary and tertiary roots were found in declining numbers down to 4 m depth

Table 3.5 Potential annual water deficit at several centres of oil palm cultivation, using IRHO methods and constants for evapotranspiration and for available soil water

Centre	Mean annual rainfall (mm)	No. of years measurements	Water deficit (mm)		
			Mean	Highest	Lowest
Pobé, Benin (Dahomey)	1,201	32	520	1,041	269
NIFOR, Nigeria	1,916	33	355	465	164
La Mé, Ivory Coast	1,993	22	254	703	28
Yangambi, Congo	1,835	20	24	165	0
Bagan Datoh, W. Malaysia	1,837	10	169	375	0
Ulu Remis, W. Malaysia	2,300	14	5	67	0
Mostyn, E. Malaysia	2,322	18	12	158	0
San Alberto, Santander, Colombia	2,453	11	129	281	0

After Hartley (1988).

Table 3.6 Mean monthly water balances, with and without runoff calculation, over 5 years for mature oil palm on Rengam series soil at Balau estate, Malaysia

	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
<i>Without runoff.</i>													
Mean rainfall (A), (mm)	73.4	35.8	228.4	252.8	38.1	98.3	145.7	291.0	118.9	381.6	239.9	280.0	2,183.9
Available water at t1 (AW1), (mm) ^a	130.0	79.4	0	73.4	130.0	41.0	10.3	28.9	130.0	116.9	130.0	130.0	
Pot. Evapotranspiration (Eo), mm	124	139	155	129	127	129	127	133	132	124	114	81	
Real available water at time t2 (AW2), mm	79.4	0	73.4	130.0	41.0	10.3	28.9	130.0	116.9	130.0	130.0	130.0	
AW2 = AW1 + A – Eo													
(Note: negative numbers imply loss of more water than the AWC. The real AW2 in this case is (0). AW2 values above AWC (130 mm) imply drainage down to this value).													
Potential Soil Water Deficit (PSWC) = AW2 – AWC	–50.6	–154.0	–56.6	+67.2	–89.0	–119.7	–101.1	+56.6	–13.1	+244.5	+125.9	+199.4	
(Note: this can be taken as a measure of the potential intensity of the drought, with reference to Field Capacity)													
Deficit below Wilting Point	0	–24	0	0	0	0	0	0	0	0	0	0	–24
Surplus over Field Capacity	0	0	0	67	0	0	0	57	0	245	126	199	694
<i>With measured runoff</i>													
Mean runoff (B), (mm)	11.0	2.6	55.0	84.7	0.2	26.1	33.2	61.3	43.9	147.9	86.3	107.5	659.6
Effective rain (C = A – B)	62.5	33.2	173.4	168.1	37.9	72.2	112.5	229.7	75.0	233.7	153.6	172.5	1,524.3
Available soil water AW1, (mm)	130.0	68.5	0	18.4	57.5	0	0	0	96.4	39.3	130.0	130.0	
Real available water at AW2 = AW1 + C – E (mm)	68.5	0	18.4	57.5	0	0	0	96.4	39.3	130.0	130.0	130.0	
Potential soil water deficit	–61.6	–167.6	–111.6	–72.5	–161.7	–186.8	–144.6	–33.6	–90.7	+19.0	+39.6	+91.9	
Deficit below Wilting Point	0	–38	0	0	–32	–57	–15	0	0	0	0	0	–141
Surplus over Field Capacity	0	0	0	0	0	0	0	0	0	19	40	92	150

The calculation assumes that potential evapotranspiration occurs at all times, and that the effective rooting depth is 1 m.

After Kee *et al.* (2000, and pers. comm.).

^aWater-holding capacity for Rengam soils = 130 mm per m depth. Eo based on open pan evaporation with crop coefficient of 1.

(see Section 11.2.1.1), and water was removed down to at least 5 m depth. These root systems were extensive and well grown, containing 31.5 t/ha of dry matter. There is a suggestion that palms in areas with dry seasons have much larger root systems or root/shoot ratios than palms in uniformly wet regions. This work shows that the arbitrary depth of 200 cm as the limit for extracting available water is much less than the real value in some soils.

3.2.3 Water relations and palm yield

It is not easy to relate oil palm yield directly to water supply, but the study of the response of palms to irrigation may be a good way of understanding this (see Section 10.3.1.2). Goh (2000) noted the difficulty of accurately relating rainfall to yield level (Table 3.7). He considered that the optimum daily evapotranspiration for the palm was 5–6 mm, and that any supply less than

this would indicate that the plant suffered from water stress. Foong (1993) used a lysimeter to show that about 5–5.5 mm per day was evapotranspired on average when the palm was mature, but the limits were from 3.0–3.5 up to 6.5–7.5 mm, depending on the weather. Kee (1995) studied the general rainfall pattern and the corresponding palm FFB in peninsular Malaysia, and these were generally in agreement with the above.

In different soils the same value of the water deficit can have different effects on plants. The ability of roots to absorb water depends on the potential or suction of the water held in the soil (Tinker and Nye, 2000). In soils with the same amount of available water the potential depends on the *soil moisture characteristics* (the graph showing the relation between the potential and the quantity of water in a volume of soil). The rate at which water can be transferred also depends on the number of water-filled pores in the soil, so that the process of water uptake is quite complicated. Simple and accurate relationships cannot therefore be expected.

The distribution of the water deficit with time may also be very different in different years, as shown in the very variable drought incidence in Lampung province in Indonesia (Fig. 3.2) (Caliman and Southworth, 1998). The relationship between the deficit and the yield is therefore unlikely to be simple, but it must be defined as far as possible. A search for such relationships between the water deficit and palm growth and yields can be made using statistical models. Early work in West Africa (Hartley, 1988) suggested that an additional water deficit of 100 mm (IRHO method) in the year of harvest reduced yield by 10%. In fair agreement,

Table 3.7 Estimated FFB yield on good soils in Peninsular Malaysia, in relation to the characteristics of the dry season

Rainfall region	Peak FFB yield (t/ha per year)
No dry season	>38
Short, fairly regular dry season	35–38
Clear, regular dry season	28–33
High rainfall throughout the year	30–35

After Goh (2000) and personal communication.

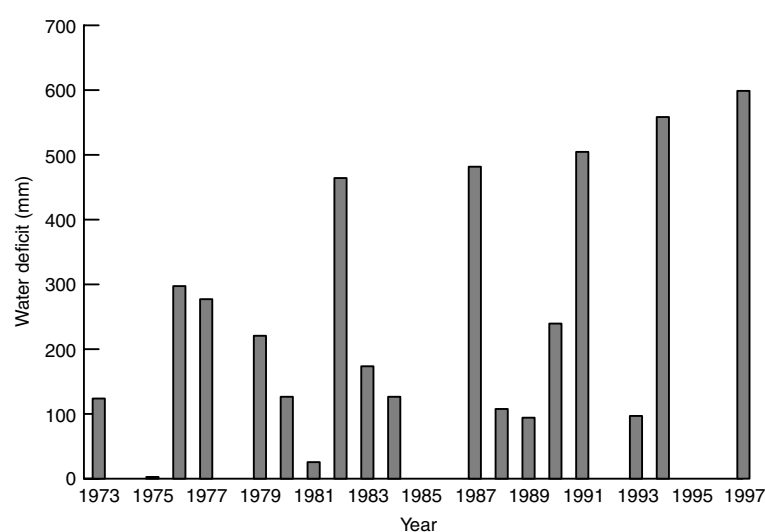


Fig. 3.2 Variability of drought, as measured by water deficits (IRHO method), in Lampung, Indonesia. (After Caliman and Southworth, 1998.)

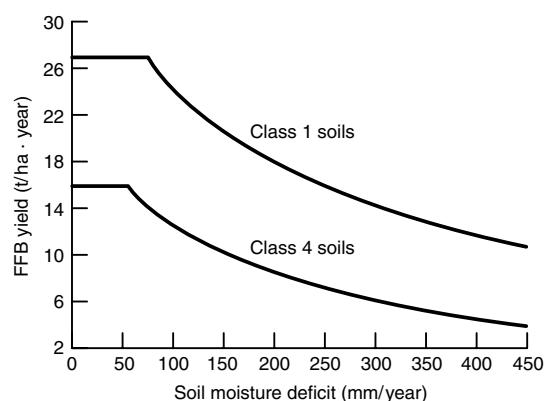


Fig. 3.3 Effect of soil moisture stress (IRHO water deficit) on FFB yields of oil palms, on two classes of soils as defined by Olivin (1968). (After Goh, 2000.)

Olivin (1968) and Ochs and Daniel (1976) found that a 100 mm water deficit reduced FFB yield between 10 and 20%, depending on the soil quality. The general relation between the annual water deficit and the yield 28 months afterwards is shown in Fig 3.3 (Goh, 2000; Olivin, 1968; Hartley, 1988; Quencez, 1996). The quality of the soils mitigates the effect of the water deficit, so that the drought effect appears at 75 mm/yr for class 1 soils, but at 50 mm/yr for poorer class 4 soils (Olivin, 1968). Later and more complex models (Dufour *et al.*, 1988; Caliman, 1992) tested the effect of the annual water deficit over the 3 years before the harvest year. Again, they found that a 100 mm deficit corresponded to a loss of about 10% of the potential yield when there was no deficit.

Caliman and Southworth (1998) pointed out that a rather different approach is needed where there are regular recurrent seasonal droughts whose consequences interact in their effects on the palm, as in West Africa, compared with where isolated droughts occur at irregular intervals, as in parts of South-east Asia (Fig. 3.2). They reported that 100 mm of deficit produced effects on FFB yield via lagged effects on floral initiation (1–3), sex differentiation (3–4) and abortion rate (8–10), where the figures in parentheses are the crop loss per 100 mm deficit, expressed as a percentage of the existing FFB yield. Overall, for single droughts they found a weak linear relationship between the yearly water deficit over the range 0–600 mm and the actual FFB harvest (Fig. 3.4). They concluded that a deficit of 100 mm in a given single year decreased FFB yield by 8–10% in the first following year and by 3–4% in the second year. The questions raised by the distribution of

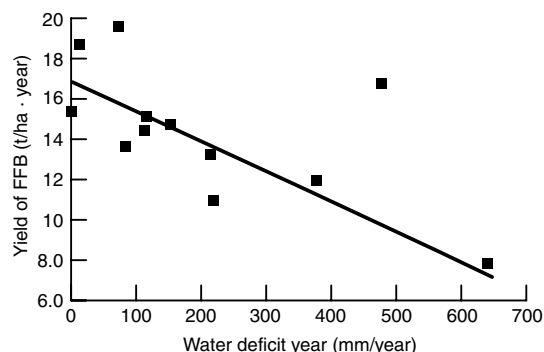


Fig. 3.4 Yield of FFB/ha in relation to annual water deficit (IRHO). (After Caliman and Southworth, 1998.)

rainfall during the year have been summarised in a simple way by Goh (2000) in Table 3.7.

3.2.4 Radiation and its effects

The importance of a high level of radiation for growth and FFB production by palms is shown by a series of simple observations. Shading palms of all ages reduces growth and net assimilation rate (Section 4.3.6). For adult palms, shading reduces the production of female inflorescences, whereas pruning the leaves of adjacent palms, so as to reduce shading, increases female inflorescence production (see Section 4.3.6.3).

Solar radiation is composed of a range of wavelengths, and roughly half the total solar radiation energy is effective in photosynthesis (see Chapter 4). Units of radiation are either GJ/m^2 per day or kcal/cm^2 per day, where there are 4.18 J in a calorie. The rate at which carbon dioxide is fixed by a green leaf increases with the radiation incident upon it. The relationship between photosynthesis rate and radiation is curved, so that increasing radiation is progressively less effective, and eventually it reaches a level when the leaf photosynthetic system is said to be saturated. A mature oil palm growing in normal density planting intercepts some 70% of the sun's total radiation (Henson, 1995a) and 90% of the photosynthetically active radiation. Henson (1999a) stated that interception of radiation is not normally rate limiting in mature oil palms. Leaves that are at the top of the canopy and at right angles to the radiation will certainly be saturated when the sun is shining, but lower leaves will largely be unsaturated and their photosynthesis rate will alter with the solar radiation. Corley (1976c) noted that the total solar radiation that is intercepted by the palm leaves sets the limit for the maximum dry matter formation that can occur, i.e. it is

Table 3.8 Sunshine (h/day) at centres of oil palm cultivation

Centre	Lat. and long.	No. of years	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual (h/day)	Total
Asia																
<i>Peninsular Malaysia</i>																
Kuala Lumpur	3°7' N, 101°42' E	17	6.2	7.4	6.5	6.3	6.3	6.6	6.5	6.3	5.6	5.3	4.9	5.4	6.1	2,230
Chemara, Johore	1°15' N, 103°30' E	11	5.5	5.9	6.3	5.8	5.9	5.7	5.7	5.5	4.5	4.6	4.0	5.3	5.3	1,940
<i>Sabah</i>																
Mostyn	5° N, 118°5' E	24	5.9	6.5	7.0	6.9	6.1	5.8	6.1	6.2	5.8	5.6	6.3	5.7	6.2	2,245
<i>Sumatra</i>																
Medan	3°35' N, 98°41' E	21	5.4	7.1	7.0	7.2	7.7	8.1	8.1	7.5	7.0	6.2	5.9	5.4	6.9	2,508
Africa																
<i>Sierra Leone</i>																
Njala	8°6' N, 12°6' W	32	7.2	7.3	6.7	6.1	6.0	5.1	2.9	2.0	3.5	5.6	6.1	6.4	5.4	1,971
<i>Ivory Coast</i>																
La Mé	5°3' N, 3°5' W	28	5.6	6.4	6.3	6.5	5.5	3.5	3.3	2.6	3.0	4.9	6.0	5.8	5.0	1,819
<i>Benin</i>																
Pobé	6°6' N, 2°4' E	24	5.5	5.8	5.3	5.5	5.6	4.3	3.0	2.4	2.9	4.5	6.0	5.9	4.7	1,721
<i>Nigeria</i>																
NIFOR, Benin	6°30' N, 5°40' E	15	5.6	6.0	4.9	5.3	5.4	4.2	2.6	2.4	2.6	4.2	6.0	6.4	4.6	1,692
<i>Cameroon</i>																
Idenau	4°5' N, 9°10' E	9	5.2	6.7	4.7	5.0	4.7	2.6	1.6	1.0	1.3	2.4	3.5	4.5	3.6	1,306
<i>Congo</i>																
Yangambi	0°49' N, 24°29' E	10	6.6	6.8	6.0	6.1	6.0	5.5	5.0	4.4	5.2	5.1	5.5	5.7	5.6	2,054
Kiyaka	5° S, 19° E	6	5.1	5.2	4.7	5.5	6.8	8.9	8.3	7.8	6.4	6.1	5.5	4.8	6.3	2,287
America																
<i>Brazil</i>																
Pará																
Paricatuba, Belém,	1°16' S, 48°8' W	15	4.3	3.6	3.6	4.1	5.5	7.2	7.7	8.2	7.5	7.8	7.2	6.2	6.1	2,220
Iguape, Bahia	12°30' S, 39° W	4	7.1	8.2	6.9	6.3	4.6	4.5	4.6	6.4	7.1	7.6	7.7	5.6	6.4	2,323
<i>Colombia</i>																
Aracataca	10°35' N, 74°9' W	13	8.6	8.6	8.8	7.7	7.2	6.8	7.8	6.9	7.1	7.2	6.9	8.4	7.7	2,792
San Alberto	7°40' N, 73°30' W	4	7.3	5.4	3.8	4.6	5.3	5.3	6.4	6.0	6.0	6.0	5.1	7.0	5.7	2,070
Rio Mira, Tumaco	1°30' N, 78°40' W	5	3.5	4.0	3.9	4.2	3.7	3.5	4.6	4.5	2.4	2.8	3.0	3.2	3.5	1,285
<i>Ecuador</i>																
La Concordia	0°05' N, 79°20' W	10	2.4	2.8	3.3	3.7	2.7	1.8	2.2	1.7	1.4	1.4	1.3	1.9	2.2	808
<i>Honduras</i>																
San Alejo, Tela	15°40' N, 87°40' W	10	6.1	6.5	8.0	8.2	7.9	7.0	7.3	7.8	6.7	6.5	5.7	5.5	6.9	2,533

After Hartley (1988).

rate limiting for growth. However, this will be decreased by a deficiency of either water or nutrients (see Section 4.3.2), and in this situation radiation is no longer rate limiting to growth. Even when there are no deficiencies, the relationship between radiation intercepted and the amount of FFB formed is not linear (Corley, 1973b), and will depend on the demand of the vegetative parts for photosynthate, that seems to have priority.

A theoretical model was used by Chan (1991) to deduce that in Malaysia a decrease of solar radiation from 6.23 to 5.69 GJ/m² per year caused a yield loss of 2.6 t FFB/ha per year. It is generally considered that palms need 5 h/day of sunshine, provided that the sunshine does not occur during a drought (Hartley, 1988) (Table 3.8). Sometimes sunshine hours are used as rough measure of solar radiation, because they are easier to measure than radiation, and they are normally well correlated. However, this is not always so. Thus, at NIFOR in Nigeria it was noted that at some times of the year the relationship with time was actually inverse, because in winter the sky was hazy with dust from the Sahara, brought in by the Harmatan wind (Fig. 3.5). In such cases radiation is the preferred variable. However, total sunshine hours per year have been correlated with annual yield, with a displacement of 28 months (Hartley, 1988).

The possibility that haze can significantly reduce radiation intensity is an issue in Malaysia and Indonesia. During droughts in the El Niño years 1997 and 1998, smoke and dust from forest fires covered large areas.

Caliman and Southworth (1998) showed that global radiation varied from 6.7 to 13.2 MJ/m² per day over a 2 week period in 1997. They found good correlations between global radiation values over the few weeks immediately before harvest and the oil extraction ratio (OER) in one oil palm factory in Riau in Indonesia. However, the haze and the severity of drought were confounded, so it is difficult to be sure how much of the effect was due to drought and how much to haze. This is discussed in more detail in Chapter 10. Henson (2000) deduced from his modelling work that haze might not reduce yield (see Section 4.1.4).

3.3 TOTAL CLIMATE AND OIL PALM GROWTH

3.3.1 Climatic requirements for the oil palm

It is difficult to determine the climatic limitations by comparing the FFB yields in different regions or countries, because so many other factors may enter into this comparison. In particular, the changes in FFB yield will not be a linear function of changes in solar radiation, which determine potential total photosynthesis (see Chapter 4) (Corley, 1973b). The requirement for solar radiation cannot therefore be known exactly. It is particularly difficult to state the requirements of the oil palm in seasonal climates, where monthly water deficits

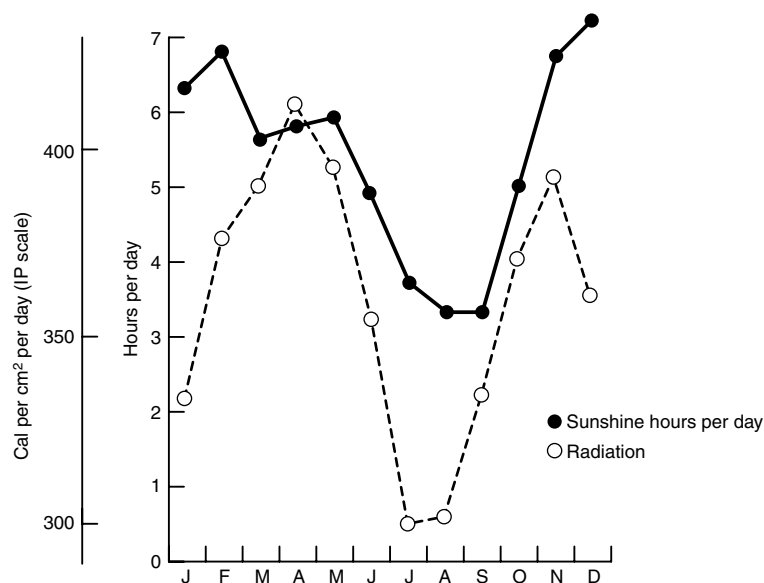


Fig. 3.5 Comparison of sunshine hours per day and total radiation at NIFOR, Benin, Nigeria, 1958–1963 (Hartley, 1988).

vary widely (Kee *et al.*, 2000) (Table 3.6), and a large annual rainfall may not compensate for poor distribution, if rainy months have little sunshine. The general conclusions are as follows.

The ideal requirements are (Hartley, 1988):

- annual rainfall of 2000 mm or greater, evenly distributed, without a marked dry season, and preferably at least 100 mm in each month
- a mean maximum temperature of about 29–33°C and a mean minimum temperature of about 22–24°C
- sunshine of 5–7 h/day in all months and solar radiation of 15 MJ/m² per day.

Goh (2000) made a similar general list:

- annual rainfall of 2000–2500 mm
- relative humidity above 85%
- low vapour pressure deficit
- no extreme temperatures or windspeed
- adequate sunshine hours and solar radiation of 16–17 MJ/m² per day.

This was allied to a requirement for high fertility, and no limitation to root development.

Goh (2000) compared data on rainfall and FFB yield from a number of countries (Table 3.9). The relationship between them was only moderately good, as is to be expected, but overall FFB yields were relatively poor with rainfalls of less than 2000 mm/year, or several dry months. Table 3.7 shows how less regular rainfall limits the highest FFB yields in Malaysian plantations (Goh, 2000). Chow (1992b) investigated the statistical correlations of rainfall with yield in Malaysia. The seasonal change explained 55% of the yield variation, with the effect of rainfall having a lagged effect of 12–24%. Rainfall 2 months before harvest had a negative effect, possibly because of the loss of radiation. Any rainfall limitation must depend to some extent on the waterholding properties of the soils. A more complex list of important climatic conditions for palms is given in Table 3.10 (Goh, 2000, after Paramanathan *et al.*, 2000).

Other authors give slightly different limits, although the differences are not large. Thus, Lubis and Adiwiganda (1996) specified that rainfall should be between 1500 and 2500 mm equally distributed around the year. They considered that more than 2 consecutive

Table 3.9 Typical FFB yields in various countries, with the local rainfall

Country	Site	Rainfall (mm/year)	FFB yield (t/ha per year)
Malaysia	Teluk Intan, Perak	2,420	37.9
	Paloh, Johore	2,010	35.0
	Tampin, Malacca	1,580	30.9
	Bintulu, Sarawak	3,400	28.9
Indonesia	West Sumatra	–	30.0
	North Sumatra	2,890	35.1
Papua New Guinea	Kimbe	3,870	30.8
	Popondetta	2,640	31.5
	Bialla	5,400	21.4
Costa Rica	Quepos (SE)	3,920	29.5
	Quepos (NW)	2,880	23.0
	Coto	4,040	26.0
Honduras	San Alejo	2,740	29.6
Benin	Pobé	1,100	13.2
	Akpadanou	1,010	9.7
Columbia	Unipalma	2,500	26.7
Congo	Lokutu	1,700	19.8
	Yaligimba	1,760	13.9 ^a
Ivory Coast	La Mé	1,480	21.8
Nigeria	–	2,000	16

After Goh (2000).

^aHigh incidence of *Fusarium* wilt.

Table 3.10 Proposed classification of climatic properties in relation to suitability for oil palm cultivation

Climatic element	Highly suitable	Suitable	Moderately suitable	Currently unsuitable	Permanently unsuitable
Annual rainfall (mm/year)	2,000–2,500	2,500–3,000 1,700–2,000	3,000–4,000 1,400–1,700	4,000–5,000 1,100–1,400	>5,000 <1,100
Duration of dry season (month)	0	1	2–4	5–6	>6
Mean annual temperature (°C)	26–29	29–32 23–26	32–34 20–23	34–36 17–20	>36 <20
Daily solar radiation (MJ/m ²)	16–17	17–19 14–16	19–21 11–14	21–23 8–11	>23 <8
Wind (m/s)	<10	10–15	15–25	25–40	>40

After Goh (2000).

Table 3.11 Agroclimatic zones for oil palm cultivation in Indonesia

Zone	Characteristic	Distribution	ASU
I	Rainfall 1,750–3,000 mm; <1 dry month; sunshine duration 6 h/day	Eastern part of North Sumatra; eastern part of Aceh; northern of Riau; northern and southern part of Kepala Burung Irian Jaya; north coast of Irian Jaya; southern part of Irian Jaya	AS1-n
II	Rainfall 1,750–3,000 mm; 1–2 dry months; sunshine duration 6 h/day	Most of Riau; eastern Jambi; most of northern part of South Sumatra; most of central Kalimantan; Aru Islands of Irian Jaya; small part of southern Irian Jaya	AS1-k1
III	Rainfall >3,000 mm; <1 dry month; sunshine duration 5.0–5.5 h/day	Western part of Aceh; western part of North Sumatra, Nias Island, northern part of West Sumatra	AS2-m2
IV	Rainfall >3,000 mm; 1–2 dry months; sunshine duration 6 h/day	West Kalimantan; most of western part of Irian Jaya	AS2-h1k1
V	Rainfall >3,000 mm; 1–2 dry months; sunshine duration 5.5–6.0 h/day	Southern part of West Sumatra; northern part of Bengkulu	AS2-h1k1m1
VI	Rainfall 1,450–1,750 mm; 1–2 dry months; sunshine duration 5.0–5.5 h/day	Small area of northern part of East Kalimantan; central Sulawesi (except Palu and surroundings); northern part of Maluku	AS2-h1k1m2
VII	Rainfall 1,450–1,750 mm; 2–3 dry months; sunshine duration 5.0–5.5 h/day	Southern part of South Sumatra, Bangka and Belitung; eastern Lampung; most of East Kalimantan; small area of eastern part of central Kalimantan; most of South Sulawesi; southern part of Irian Jaya borders with Papua Nugini	AS3-h1k2m2
VIII	Rainfall 1,750–3,000 mm; 3–4 dry months; sunshine duration 5.0–5.5 h/day	Western part of Lampung; small area of western part of West Java	AS3-k2m2
IX	Rainfall 1,250–1,450; 3–4 dry months; sunshine duration 5.5–6.0 h/day	Palu and surroundings; most of Sulawesi Tenggara; central Maluku; South Maluku; East Timor	AS3-h2k2m1
X	Rainfall 1,250–1,450 mm; >4 dry months; sunshine duration 6 h/day	Eastern part of West Java; central Java; East Java; Bali; southern part of South Sulawesi; southern part of Sulawesi Tenggara	ANS-h2k3
XI	Rainfall <1,250 mm; >4 dry months; sunshine duration 6 h/day	West Nusa Tenggara; East Nusa Tenggara	ANS-h3k3

After Adiwiganda *et al.* (1999).

ASU: Agroclimatic suitability unit; AS: agroclimatically suitable; ANS: agroclimatically not suitable; n: normal (without any limiting factor); h: rainfall as limiting factor; k: dry month as limiting factor; m: sunshine duration as limiting factor.

1: light intensity; 2: moderate intensity; 3: strong intensity.

dry months would produce a decline in yield, and more than 3 months would give a serious limitation. The largest acceptable yearly water deficit was 200 mm. The temperature should be between 22 and 33°C, and the mean daily sunshine in every month of the year should not be less than 6 h. This has been generalised by Adiwiganda *et al.* (1999), who designated 11 agroclimatic zones on their suitability for oil palms in Indonesia (Table 3.11). The basis is rainfall, sunshine hours and length of dry periods, and the table systematises the information on how these factors affect oil palms. No more than 1–2 dry months are acceptable for the top two 'suitable' categories. Siregar *et al.* (1998) produced a table of agroclimatic suitability classes that are basically similar, but in which elevation was also included as an important parameter. This is regarded as a negative factor if greater than 200 m, and is really an effect of low temperature. There is thus a good basis of general climatic information to guide site selection in Indonesia.

The limitations on the climate that are acceptable to the oil palm are seen most clearly in west and central Africa, because of the range of wet season and rainfall found there. Quencez (1996) showed the various levels of low-temperature frequency over the whole area (Fig. 3.1). In West Africa the high rainfall belt is very narrow, so that acceptable areas, with maximum deficits of 200 mm or less of water, are confined to the coastal areas. The long dry season in southern Benin has tended to increase, whereas the short dry season has diminished (Yao *et al.*, 1995; Nouy *et al.*, 1999). The result is that cumulative monthly water deficits may reach annual deficits of 400–700 mm (maximum

900 mm), and these may kill the palms. The corrective action recommended was to choose planting sites with care, use a low planting density and prune the palm crowns (Section 3.5.2.2). The yields under these conditions were not reported.

In central Africa the climatic belts are wider, and successful oil palm plantations can operate in the Congo, even though it suffers from rather low minimum temperatures. Low levels of radiation occur in many areas that have reasonable annual water deficits, in part because of the small number of sunshine hours during intense wet seasons, but the effect of seasonal droughts within the apparently reasonable annual deficit is probably greater. Thus, very small numbers of sunshine hours have been recorded in Ecuador (Hartley, 1988, p. 108; Mite *et al.*, 2000), but the yields are consistently greater than in West Africa. The effect of 3 months' drought is therefore greater than that of a 50% reduction in sunshine hours. The existence of a dry season reduces yields even where the total rainfall exceeds 2000 mm (Hartley, 1988). In total, virtually no other area has the full combination of favourable conditions that are found quite widely in South-east Asia.

The differences in the yield levels in West Africa and in South-east Asia are well known in general. However, in earlier comparisons different planting materials were always used, with different levels of agronomic care, so it was difficult to make precise comparisons. Nouy *et al.* (1999) planted the same cross in 20 experiments in typical conditions in Indonesia, Ivory Coast and Benin, and the yields in these 6–10-year-old plantings are shown in Table 3.12. The bunch components and oil/bunch did not differ greatly, but the yields, bunch numbers and

Table 3.12 Comparison of yields from a single cross (LM2T × DA10D) planted in three different zones with differing climates, in 20 trials with palms 6–10 years old

	Aek Kwasan, Indonesia	La Mé, Ivory Coast	Akpadanou, Benin
Mean annual WD (mm)	50	350	550
Number of trials	10	8	2
FFB production/year (kg/palm)	205	110	50
Number of bunches/year	16.6	10.4	6.0
Bunch weight (kg)	12.4	10.0	8.2
Peak production (%) ^a	13–16	17–23	35–43
% OER	22.5	20.4	21.8
% Fruits/bunch	61	60	60
% Mesocarp/fruit	79	78	78
% Oil/mesocarp	54	52	55

After Nouy *et al.* (1999).

^aExpressed as a percentage of annual production.

WD: water deficit; FFB: fresh fruit bunch; OER: oil extraction rate (outside dry season).

bunch weights all declined sharply as the soil water deficit increased. Dufrene *et al.* (1990) earlier concluded that in addition to the water deficit effect, the higher vapour pressure deficit in the atmosphere and the lower sunlight levels in West Africa both contributed to the yield differences between there and South-east Asia.

3.3.2 Longer term weather variations

Interest has recently increased in the interannual variation. With the recognition of major climatic variations such as El Niño (southern oscillation), which determine many of the extreme climatic occurrences in the southern hemisphere, the possibility of cautious prediction of weather in following years has increased. At present, understanding is still not sufficient to allow prediction of El Niño events, or their severity, but intensive work is being done in this subject (Glantz, 2001).

Longer term variation is usually called 'climate change' or more generally 'global change'. In the distant past the world's climate changed repeatedly and extensively, although the last 10,000 years appear to have been unusually stable. The climatic change now being discussed is anthropogenic, being caused by the increased output of greenhouse gases from the use of fossil fuels and the net loss of forest. The exact importance of the latter process is still in considerable doubt and for a long time there has been a 'missing sink', which has to be postulated to balance the world's carbon economy (Scholes *et al.*, 1999). However, it is certain that there is a net loss of tropical forest, partly because of the conversion of forest to plantations or farms (Tinker, 1997; Gregory *et al.*, 1999) and partly because of logging, although these processes are often combined (Casson, 2000). Data in Casson (2000) and Sargeant (2001) show the impact of oil palm development in Indonesia, as described in Chapter 1.

It is fairly certain that climatic change can already be detected, with significant rises in the world's mean surface temperature, especially during the 1990s (IPCC, 2001). The coming change over the next century is predicted to be of the order of 1.5–5°C, but the temperature changes will be least at the equator and greatest near the poles, so this is not likely to affect the oil palm regions much. It is likely that the most important impacts will be on rainfall, and this is the most difficult climatic parameter to predict. Rainfall should increase because a higher air temperature means that on average the air will have a higher moisture content, but precise, area-specific prediction is only just becoming possible. The effect of global change on tropical forests is mainly

due to land-use change, of which establishment of oil palm plantations is one example. Such changes may have very significant effects on biodiversity (Sala *et al.*, 2000), although the prediction is very sensitive to the assumptions made.

The oil palm industry thus has a double interest in this subject of climate change. The expansion of oil palm plantations has some small part in the causative processes, and the consequential climatic change will affect the industry by changing the suitability of different countries for cultivating oil palms.

3.3.3 Country and region experience

The very successful results of oil palm cultivation in the two big producers in South-east Asia, Malaysia and Indonesia, have caused plantation industries to be developed in neighbouring countries with similar climates. There is evidence of lower yields due to shortage of rainfall (Henson and Chang, 1990) in some of these neighbouring regions. Thailand is now a large producer, but the climate is less favourable than that in Malaysia, as the country is well north of the equator, except for the southern province. Rainfall is not well distributed and irrigation is sometimes necessary. Palat *et al.* (2000) showed that at a site in southern Thailand 8° north of the equator, open pan evaporation exceeded rainfall between December and March, with an average water deficit (calculated according to IRHO) of 214 mm. Papua New Guinea has a good climate, but the rainfall in many parts is very heavy, at 4000–5000 mm. There is consequently a deficiency of sunshine, but very good yields have been obtained.

By contrast, Benin in Africa has a dry season of 4 months, and the rainfall at Pobé is only 1232 mm. The yields are consequently both low and highly variable, with a very poor year every 4–6 years. Drought is the essential problem, as shown by the fair yields obtained with irrigation or a high water table. In the Nigerian oil palm belt the dry season varies from barely 1 month in the south-east to 3 months in the north-west of the region, with the amount of rainfall varying in parallel.

Some of the American regions have marked dry seasons. For example, in the north of Colombia there are almost 5 months with minimal rain, and the annual rainfall is in the region of 1000–1600 mm. Fortunately, there are high water tables in many areas. A similar situation holds in the Palma-Sola area of Venezuela. Costa Rica also has a lengthy dry season, but the total rainfall is more than double that in Colombia, at 3300 mm.

Despite high water tables, the seasonal climate produces a seasonal change in yields similar to that in West Africa, and long droughts can occur (Villalobos *et al.*, 1992).

3.4 SOILS

3.4.1 Soil classification in the equatorial tropics

Soils are variable and complex. There are considered to be five soil-forming factors (climate, parent material, topography, vegetation and age), to which human intervention and use has to be added. As each soil-forming factor varies widely over the surface of the Earth, it is hardly surprising that soil description and classification is difficult and complicated, and continues to cause much argument.

3.4.1.1 Types of classification

There are two main types (Wild, 1988; Paramanathan, 1995; White, 1997). First, there is the classification in which the empirical objective is to define the suitability for a single use, e.g. planting oil palms. These classifications can be very useful over limited ranges of distance and climate, but usually break down when applied to conditions different to those in which the classification was originally developed and tested. They may require a great deal of work to develop a classification that has only one use, and sometimes they may appear to be little more than a formalisation of the local experience of agronomists.

The second type is the general-purpose classification, which aims to set up a system that is in principle applicable to all soils, and is based on their intrinsic properties. The selection of these properties, and the degree of their internal correlation and consistency, determine the success of the classification, which is tested in practice by finding that all soils can be accommodated within it, and that soils classified similarly behave similarly. This can be a somewhat academic exercise, and for practical application it is necessary to identify soil classes that are associated with desirable results. It is normal that local soil surveyors will have identified and named soil series empirically during their early surveys, so that the names of these become the basis of local soil map legends, and their practical value is known from experience. Ideally, these series can be allocated to the classes in a later general-purpose classification, so that the existing practical information is integrated into the classification.

3.4.1.2 Current general-purpose classifications

In the early part of the twentieth century tropical soil classifications were mainly of the first type, and of limited application, and any general-purpose classification was simple, and often a direct extension of temperate soil classification. With time, two major general-purpose classifications have become dominant (Sanchez, 1976). The first is the United States Department of Agriculture Soil Taxonomy (Soil Survey Staff, 1975) system, with the latest Key to Soil Taxonomy (USDA, 1996). This was based on an original concept, which gave very precisely defined soil units. It also produced a huge number of new technical terms, which makes it difficult to use, both for those who are not professional soil scientists and for some of those who are. The second main system was based on the legend of the 1974 FAO–UNESCO World Soil Map (FAO–UNESCO, 1988). This included more of the older terminology, and is probably easier to use for general purposes by those who are not professional pedologists. Nevertheless, many oil palm agronomists do now use the Soil Taxonomy system, but often with some local modification. The relationship between the classes in the Soil Taxonomy system, the FAO legend classification and other systems' terminologies, including the French, Brazilian and the Belgian (Congo) systems, has been tabulated by Sanchez (1976, p. 56 ff.). Usually an approximate synonym can be found in another classification system. A set of synonyms for the two major classifications, with brief class descriptions, was given by Nortcliff (1988) (Table 3.13).

The use of these general classifications for the determination of the value of a soil as an oil palm plantation is not easy. Paramanathan (1995) gives a very clear explanation of the different levels of detail of soil survey. The FAO–UNESCO is the simpler of the two, but its 26 world groups are far too broadly defined to determine soil use. This is simply a consequence of the range of natural soil properties. In practice, one has to go down to the family level at least to define the properties that could determine plant growth. Most of the diagnostic properties by which soils are distinguished were selected for ease of determination or observation and for clarity of separation between soils, rather than for their importance to vegetation. It can be hoped that the diagnostic properties are correlated with soil use and value, but this has to be tested by experience. It would be unusual for a factor of direct agronomic importance, such as the concentration of nutrients, to be selected as an important criterion for that reason.

In older work, almost all tropical oil palm soils were described as 'latosols', and this was used as the basis of soil description in earlier editions of this book (Hartley, 1988). These were defined as the predominant soils of the humid and subhumid tropics, found at elevations from 0 to 2000 m, with annual rainfall of 250–10,000 mm and under a great variety of vegetation (Sanchez, 1976). This term was so all-embracing that it was of little use in practice, and it is hardly used now.

The earlier linkage between the genetic process in which a soil was believed to be formed and its classification has therefore weakened, because of the uncertain inferences that have to be drawn about pedogenesis. Both of the main general classifications are

now based on the use of *diagnostic soil horizons*, and their detailed properties. Soils in the Soil Taxonomy system are given additional names relating to their moisture status: udic (well supplied), ustic (moderately well supplied, but with marked dry season), aridic (dry) and aquic (so wet that the soil has reducing conditions). Thus, soils in the well-watered oil palm areas, as in south-east Asia, will be udic or aquic, whereas those with a dry season, as in much of West Africa, will be ustic.

3.4.1.3 Soil classification in South-east Asia

The soils of Sabah and Sarawak have been reclassified relatively recently (Paramanathan, 1995, following

Table 3.13 Soil class names as used in Soil Taxonomy and FAO–UNESCO soil classification systems, with brief descriptions

FAO class	Brief description	USDA equivalent
Acrisols	Acid low base status soils. More strongly leached than Luvisols, but insufficiently leached for ferralsols. Tend to be reddish	Ultisols (part)
Andosols	Soils derived from recent volcanic deposits	Andepts
Arenosols	Coarse, weakly developed soils with an identifiable B horizon. Clay content <15%	Psamments (part)
Cambisols	Earths with cambic B horizon	Inceptisols (part)
Chernozems	Black earths of the steppes	Borolls (part)
Ferralsols	Strongly weathered soils of the humid tropics, with oxic horizon	Oxisols
Fluvisols	Recent alluvial soils	Fluvents
Gleysols	Hydromorphic soils	Aquic suborders (part)
Greyzems	Grey forest soils	Borolls (part)
Histosols	Organic soils; peats	Histosols
Kastanozem	Chestnut steppe soils. Similar to chernozem, but with shallower 'erdefication' and with carbonate/gypsum horizons	Ustolls
Lithosols	Soils of <10 cm depth over hard rock	Lithic subgroups
Luvisols	Soils with argillic B horizons and high base status	Alfisols (part)
Nitisols	Tropical soils with argillic B horizon	Some Ultisols and Alfisols
Phaeozems	Prairie soils: paler than Chernozems. Chernozem–Kastanozem intergrade.	Udolls (part)
Planosols	Soils with albic E and hydromorphic properties	No equivalent
Podzoluvisols	Soils intermediate between podzols and luvisols	Glossic. Great groups of Alfisols
Podzols	Soils with spodic B horizon	Spodosols (part)
Rankers	Shallow soils with umbric A horizon	Lithic
Regosols	Weakly developed soils from unconsolidated materials	Haplumbrets
Rendzina	Shallow calcareous soils with mollic A horizon	Orthents
Solonchaks	Saline soils	Psamments
Solonetz	Alkali soils with natric B horizon	Rendolls
Vertisols	Dark, montmorillonite-rich, cracking soils	Salic great group
Xerosols	Semi-desert soils with weak ochric A horizon (0.5–1.0% OM)	Natric great groups
Yermosols	Desert soils with very weak ochric A horizon (<0.5% OM)	Vertisols
		Mollic Aridisol
		Typic Aridisol

After Nortcliff (1988).

earlier work (Paramanathan, 1987a; Acres *et al.*, 1995; Scott, 1973). These classifications are now extremely detailed, all being based on the US Soil Taxonomy principles. The soil surveys and earlier classifications of Peninsular Malaysia, Sabah and Sarawak, and a translation of the Indonesian classification system, are in Paramanathan (1995). The initial classification on the basis of parent material in Peninsular Malaysia is shown in Fig. 3.6 (Paramanathan, 1995). The surface geology in Sabah is particularly complex, producing scores of soil families.

Malaysia has recently developed a well-defined new soil classification, closely based on the Soil Taxonomy principles (Paramanathan, 1998, 2000b). The terminology is in Malay, bringing in yet more disciplinary new words to learn, and almost certainly lessening its general application. A useful table in Paramanathan (1998) gives corresponding terms in the Malaysian, Soil Taxonomy and FAO–UNESCO systems. This system is now being used in Malaysia, and is being extended to Indonesia, and clearly should be the basis on which land is selected for oil palm and other crops there.

There have been problems in developing these new systems, because traditional soil surveys usually defined

a number of soil series names at an early stage, and then tended to force all soils into those series. More complexity has been introduced by reclassifying, and it is essential to bear in mind Paramanathan's (1995) advice 'not to make the Keys too complicated, as this will prevent soil surveyors from using the Keys'. This is even more true of agriculturists in general. The difficulty is that when considering an actual use, such as growing oil palms, some of the criteria on which the soil series are defined are of no importance, whereas others are essential information. Only experience of the intended use can guide the application of soil survey and soil map information.

The Indonesian system (English translation in Paramanathan, 1995) follows the USDA Soil Taxonomy system closely, but with phonetically spelled names, which seems a very sensible innovation. The oil palm soils are identified by Lubis and Adiwiganda (1996) (Section 3.5.1.2), with their Soil Taxonomy families, and they are grouped in land suitability classes, with area covered in per cent, and the expected FFB yields (Table 3.14) (Lubis and Adiwiganda, 1996). There is consequently a strong background of soil information in South-east Asia. Details of the soil surveys that have been done in the South-east Asian area (ASEAN) are given in Table 3.15 (Paramanathan, 1995).

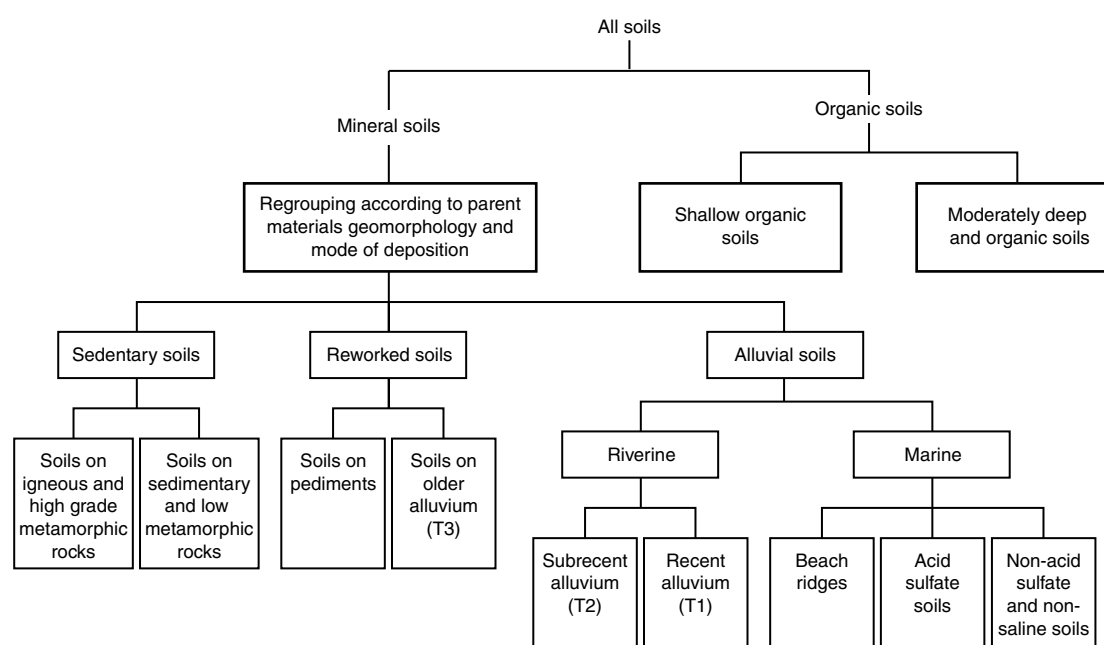


Fig. 3.6 Parent materials of Peninsular Malaysian soils (Paramanathan, 1995).

Table 3.14 Land suitability classes, with estimated FFB yields, and percentage of total oil palm area in Indonesia, based on soil classification

No.	Soil subgroup	Land suitability class		Productivity (t FFB/ha per year)	Area (%)
		Actual	Potential		
1	Eutric tropofluvent	S1	S1	>30	4
2	Typic hapludand/aquic hapludand	S1	S1	>28	1
3	Typic dystropept	S2	S1	>26	8
4	Typic hapludult	S2	S1	>24	20
5	Typic paleudult	S3	S2/S1	22–>24	25
6	Psammentic paleudult	S3/N1	S2	22–24	10
7	Typic plinthudult/plinthic paleudult	N1	S3	20–22	6
8	Typic tropopsamment	S3	S2	22–24	1
9	Aeric tropaquent	N1	S2	22–24	3
10	Aeric tropaquept	N1/S3	S2/S1	22–>30	4
11	Typic ochraqult	N1/S3	S2	22–24	4
12	Typic paleaquult	N1/S3	S3/S2	20–22	1
13	Fluvaquentic troposaprist	S3	S2/S1	22–>24	2
14	Typic troposaprist	N1	S3/S2	22–24	9
15	Hemic troposaprist	N1	S3	20–22	2

After Lubis and Adiwiganda (1996).

S1: highly suitable; S2: moderately suitable; S3: marginally suitable; N1: conditionally not suitable.

Table 3.15 Details of soil surveys within the ASEAN countries: scales and intensity of observations

Scale of survey	Country	Spacing between examination points	Area represented by each examination	Base map for fieldwork	Final soil map published
Reconnaissance	Brunei	–	0.7 sites/sq mile	1:50,000	1:100,000
	Indonesia	2 km × 1 km	200 ha	1:100,000	1:50,000
					1:1,000,000
	Malaysia	4 km × 0.5 km	200 ha	1:50,000	1:100,000
				1:63,360	1:250,000
Semi-detailed	Thailand	1 km × 1 km	100 ha	1:50,000	1:50,000
					1:1,000,000
	Indonesia	1 km × 250 m	25 ha	1:20,000	1:50,000
				1:25,500	1:20,000
	Malaysia	800 m × 200 m	16 ha	1:12,500	1:25,000
Detailed					1:50,000
	Thailand	200 m × 250 m	5 ha	1:15,000	1:25,000
	Brunei	300 m × 300 m	9 ha	–	–
	Malaysia	200 m × 200 m	4 ha	1:5,000	1:5,000
				1:10,000	1:10,000
	Thailand	100 m × 100 m	1 ha	<1:10,000	<1:10,000

After Paramanathan (1995) (see for authors and dates).

3.4.2 Soil characteristics that are important for the oil palm

3.4.2.1 System of *Olivin*

The oil palm is fortunately not very demanding in its requirements, as it tolerates quite wide variations in soil

acidity and in water status, but there are some soil types on which it may not thrive (Section 3.4.3). *Olivin* (1968, 1986) produced the earliest systematic method for assessing oil palm soils (Table 3.16) (Hartley, 1988). This was combined with a prediction of the expected FFB yield on each soil class, with various levels of water

Table 3.16 Grading of soils classes defined in terms of suitability for oil palm cultivation, based on texture, stones, drainage and chemical status

Soil class	Characteristics			
	Texture	Gravel and stones	Drainage	Chemical status
I	Sands to clays	None	Good	Organic matter: good Exchangeable cations: good
IIa	Sands to clayey sands	None or very little	Good to 90 cm	Organic matter: medium Exchangeable cations: medium
IIb	Sands to clays	Some gravel	Good to 60 cm	Exchangeable cations: medium
III	Sands to clays	Gravelly	Poor	Organic matter: medium Exchangeable cations: poor
IV	Leached sand or very heavy clay	Very gravelly	Deep peat, or very bad	Poor

After Hartley (1988). I, good; IV, poor.

supply (Hartley, 1988) (see Section 8.1.5). The system is so simple that it does not allow fine distinctions. In some cases it is unlikely that two types of properties listed in the same class would in fact be found within the same soil. Basically, a good soil is one with little gravel, a texture that allows reasonable drainage, but has still retained plenty of exchangeable cations and contains a good level of soil organic matter. The details of the system contain definitions of seven textural classes, in four levels of the profile, and six classes of gravel. pH is not a critical factor, provided it is above about 4.0. The experience has been that yield estimates based on this system for soil classes I and II are fairly reliable if there is a moderate water deficit, but with the poorer soil classes and high water deficits the yields are much less than predicted (Hartley, 1988).

3.4.2.2 System of Paramanathan

Paramanathan (2000a) has given a detailed set of criteria (Table 3.17) of suitability for oil palm cultivation, but it is better to call them land characteristics (Paramanathan *et al.*, 2000). These are designed for South-east Asia, but would probably be applicable in all similar climates. There are soils with some bad and some good characteristics, and a pragmatic approach has to be taken to using these guides. The classification system that uses the above criteria (Table 3.17) (Paramanathan, 2000a), is not fully quantitative, and depends on subjective judgement and experience to a significant extent. These characteristics can then be looked for in the soils classified by the Soil Taxonomy or any other system.

The first criterion (Table 3.17) is topography. This is discussed further in Chapter 8, because of the possible need for terracing. This system dismisses land as unsuitable for oil palms if it has a slope greater than 20°. The

‘wetness’ criterion effectively selects land that is neither excessively or insufficiently drained, nor prone to flooding. Drainage has been defined in terms of ten classes (Paramanathan, 1987b). A hydromorphic (anoxic) condition may be produced in a soil either by flooding due to a high water table, or because the hydraulic conductivity of the soil cannot allow the rainfall to infiltrate or to move down the profile. The ‘physical’ criteria are soil conditions arising from the texture of the soil material, and the presence or absence of barriers to root penetration, such as solid rock, compacted gravel or soil, or toxic chemical conditions such as an acid sulfate horizon. This includes the stability of the soil structure. In oxisols and ferralsols there is a great deal of free ferric oxide, and the soil structure consists of small but stable aggregates that give excellent stable drainage and a very beneficial structure. A poorly drained soil histosol will be hydromorphic, the iron will be reduced and leached away, and the structure will be compact or massive. The nutrients in the soil are given little attention in Table 3.17, for reasons that have been discussed earlier (Section 3.4.1).

3.4.3 Soil characteristics that are unfavourable for the oil palm

There are several soil types that are generally unsuitable for palms if they are to give high yields, although peat soils are now becoming much more widely used. The reasons for this need to be considered.

3.4.3.1 Rooting depth and density

The oil palm root system needs to be well developed, and a problem with some soil types is simply inadequate rooting volume (Section 8.1.3.3). Oil palms certainly

Table 3.17 Classification of topography, soil wetness, physical and rooting conditions, and chemical conditions in terms of suitability for oil palm cultivation

Soil characteristic	Suitability class:	Highly suitable (S1)		Moderately suitable (S2)	Marginally suitable (S3)	Unsuitable (N)
	Degree of limitation:	Not limiting	Minor limitation	Moderate limitation	Serious limitation	Very severe limitation
Topography						
Slope (%)		0–4	4–12	12–23	23–38	>38
Slope (°)		0–2	2–6	6–12	12–20	>20
Wetness						
Drainage class		Moderately well to imperfect	Well to somewhat excessive	Excessive or somewhat poorly drained	Poorly drained	Very poorly drained
Flooding		Not flooded	Not flooded	Minor flooding	Moderate flooding	Severe flooding
Physical soil conditions						
Texture/structure		Cs, SC, CL	Co, L, SCo, SiCL	SCL, Cm, SiCs	SiCm, SL, Lfs	LcoS
Depth to root restricting layer (cm)		>100	75–100	50–75	25–50	<50
Depth to acid sulfate layer (cm)		>100	–	75–100	50–75	<50
Thickness of organic soil (cm)		–	0–50	50–200	200–500	>500
Soil fertility conditions		>24	16–24	<16		
Weathering stage (effective CEC) cmol(+)/100 g clay						
Base saturation (%) A horizon		>50	35–50	<35		
Organic carbon (%) A horizon		1.5–2.0	2.0 or < 1.5			5
Salinity (millimohs) 50 cm depth		0–1	1–2	2–3	3–4	>4
Micronutrients			Deficiency	Toxicity		

After Paramanathan (2000a). C = clay; S = sand; L = loam; Si = silt; s = structured; m = massive; o = oxic horizon; f = fine; co = coarse.

can root deeply, as their roots have been observed down to several metres in the deep uniform sandy clays of southern Nigeria (Section 2.2.1.5), although the root length density (Section 11.2.1.2) is very small at depth. Almost all the fine root is in the top 1 m, with most of it concentrated in the top 30 cm (Section 11.2.1.2). Palms can grow with only 50 cm of effective soil depth, if that is well supplied with nutrients and water.

3.4.3.2 Poorly drained (hydromorphic) soils

These are aquults, aqualfs, aquepts or aquents in Soil Taxonomy, and gleysols or gleyic subunits in FAO–UNESCO terminology. There are two basic reasons for this physical state, although they may interact (Ponnamperuma, 1984). The first cause is a general water table in the surrounding area so high that most of the profile is saturated for a part of the year. However, a short-term seasonal water table may be acceptable, possibly because there will normally be relatively rapid movement of water within the soil during a rainy season,

so that there is always some free oxygen in the water and the soil does not become reduced. It is not the surplus of water, but the lack of oxygen that is damaging. If necessary, this condition can be corrected by normal drainage practices, so long as there is somewhere for the water to flow to.

It is more difficult to correct the second cause, namely poor internal drainage which occurs when a fine-textured soil has such a low water conductivity that it drains at a very slow rate, and the whole profile may remain saturated for the part of the year with high rainfall. Drainage is useful, but a dense network of drains may be necessary in such heavy soils. If a permeable surface horizon overlies very dense impenetrable clay, a perched water table may appear in the permeable horizon, and this can be removed by drainage channels. Drainage may improve after establishing treecrops, as roots slowly penetrate below the surface layer and evapotranspiration increases. These conditions are damaging because palm roots are tolerant of anaerobic soil layers only to a moderate extent, and will not penetrate deeply into them. In

addition, anaerobic conditions cause reduction of the nitrate ion, part of it being lost as gaseous nitrogen. Nitrogen deficiency is therefore a danger.

3.4.3.3 Acid sulfate soils

These are sulfaquepts and sulfic tropaquepts in Soil Taxonomy. These are poorly drained soils, often close to the sea coast, in which iron sulfide (pyrites) has been formed in the profile by reduction of the sulfate ion left behind by occasional seawater incursions. If the soil is drained so that the pyritic layers are in aerobic conditions, the sulfide will be oxidised back to sulfate ions. In the absence of a balancing cation, this is in effect sulfuric acid, and the pH can fall below 2, which is toxic to roots. A sulfate layer is defined as one containing yellow mottles of jarosite (potassium iron aluminium sulfate) and with a pH less than 3.5 when oxidised. These soils can be used for oil palms if the water level is carefully controlled to be a short distance above the pyritic layer, so as to prevent this oxidation. They were problem soils until their chemistry was properly understood (Bloomfield and Powlson, 1977) but they can now be used with care.

3.4.3.4 Saline soils

Marine clay soils and mangrove swamp soils are often saline; they often overlap with the acid sulfate soils because both conditions are connected with proximity to the sea and a low-lying situation. Where plantations are established on old mangrove soil (Toh *et al.*, 1988; Jamaluddin Nasir *et al.*, 2000) the soil solution will originally be close to the composition of seawater, and there will be a large exchangeable sodium percentage on the exchange complex. This causes soil structural weakness, and the high sodium and chloride levels may be toxic. The oil palm is not as tolerant of seawater as is the coconut palm, and it is not a halophile species (Munns, 1993). A conductivity level of 1 S/m is the maximum that can be tolerated, but saline soils are often up to 3 S/m (S stands for Siemens, the SI unit for conductivity). The management of the tidal flows has to be arranged to prevent the inflow of seawater, but to allow drainage water carrying leached sodium chloride to flow out.

Such soils require much work to bring into use, with ploughing and harrowing to level the land, and construction of drains, bunds and tide gates. Otherwise soil must be mounded around the palm bases, or the palms must be planted on ridges, to ensure that they have a sufficiently large drained rooting volume. These soils have effectively three potential constraints, which can interact: waterlogging and lack of oxygen, salinity and

exchangeable sodium, and sulfate acidity. The key to all three is the management of tidal and river flows (see Section 8.2.3), and if this is successful, 20 t/ha or more FFB yield can be obtained. Irrigation may also produce soil salinity (Section 10.3)

3.4.3.5 Lateritic soils

These are plinthudults in the Soil Taxonomy. The term 'lateritic soil' is by now confusing and rarely used. Here, it means a soil with substantial amounts of laterite or plinthite, either or both as small concretions distributed through the soil, or relatively large masses, ranging up to solid layers covering considerable areas in the subsoil, which may become exposed at the soil surface by erosion (Sanchez, 1976; Eswaran *et al.*, 1987). The plinthite is largely iron and aluminium oxides and is chemically inert. Its adverse effect on palm growth, when present in large quantities, is probably due to the loss of effective soil volume, as the plinthite does not hold plant-available water or release nutrients as decaying rock would do. If the amount of plinthite concretions is fairly small, and the properties of the soil material are good, the soil may be perfectly satisfactory, but Tan (1979) found that the total weight of root, of all ages of palms, on shallow laterite soils, was only 20–70% of that of palms of the same age on non-laterite soils elsewhere.

3.4.3.6 Deep sandy soils

These are mostly psamments in Soil Taxonomy, and regosols or arenosols in the FAO–UNESCO system. Coconuts traditionally thrive on such soils near the coast, but they are of little value for oil palms, which require a reasonable amount of clay in the subsoil. In Indonesia some soils of this type, under *Kerangas* forests, have been planted but growth has been very poor (Paramanathan, 2000a). Adiwiganda *et al.* (1993) reported on a large area (1 M ha) of spodosol (podsol) in Riau province, which suffered from two of these disadvantages: the top 40–80 cm was very sandy, and below this was a compacted spodic horizon that prevented root penetration. It was judged to be useless for oil palms. Well-structured clay, sandy clay, clay loam and silty clay loam are considered to be ideal for oil palm planting (Table 3.17).

3.4.3.7 Peat soils

These occur where a very high water table has caused organic matter accretion over many years, so that it may be several metres deep. The organic remains are

gradually decomposed into peat, which usually remains separate from the underlying mineral soil, as there are no mixing processes in these permanently waterlogged conditions. The tropical and temperate peats originate from different vegetation and have different properties (Fairhurst *et al.*, 1998), the tropical ones being classified (Soil Taxonomy) as histosols, suborder tropofibrists and trophemists (Paramanathan, 1998). Whereas temperate peat is mainly formed from mosses, tropical peat is formed from woody material that collects in permanently waterlogged areas. It decomposes gradually into a dark and fibrous mass, which continues to decompose slowly if left waterlogged, but decomposes much more rapidly if it is drained, and also shrinks physically if it dries out.

These soils, especially deep ones, were traditionally regarded as difficult to plant with oil palms (Gurmit *et al.*, 1987), despite the fact that in temperate conditions peats are often considered to be exceptionally good soils. The problems with the soils are in part nutritional, including trace element problems (Tayeb Dolmat *et al.*, 1996) (Sections 8.3.6; 11.8.4). Tropical peats are formed either in depressions in flat areas such as coastal

plains, where little input of silt can occur (ombrogenous peats), or on river flood plains where silt and nutrients are deposited in floods (topogenous peats) (Fairhurst *et al.*, 1998). The mineral nutrient content of the latter is therefore considerably higher than that of the former. Most of the large areas of peat available are ombrogenous, so a full fertilising regime is very important, including trace elements. Physical problems can also be serious, because of the lack of anchorage for the palms in peat soil of low density and poor mechanical strength, so that they lean or fall. This makes management and harvesting far more difficult. However, there is great pressure to use these soils now, as good sites on the mineral soils are becoming difficult to find in South-east Asia, and of the mineral soil areas available, many are hilly and steep. Fairhurst *et al.* (1998) suggest that there are 30,000,000 ha of deep peat in South-east Asia, and this is already being planted widely, despite many problems in earlier attempts to use it (Fig. 3.7) (Fairhurst *et al.*, 1998).

Deep peat soils in all countries pose difficult problems of management (Andriesse, 1988) (see Chapters 8, 10 and

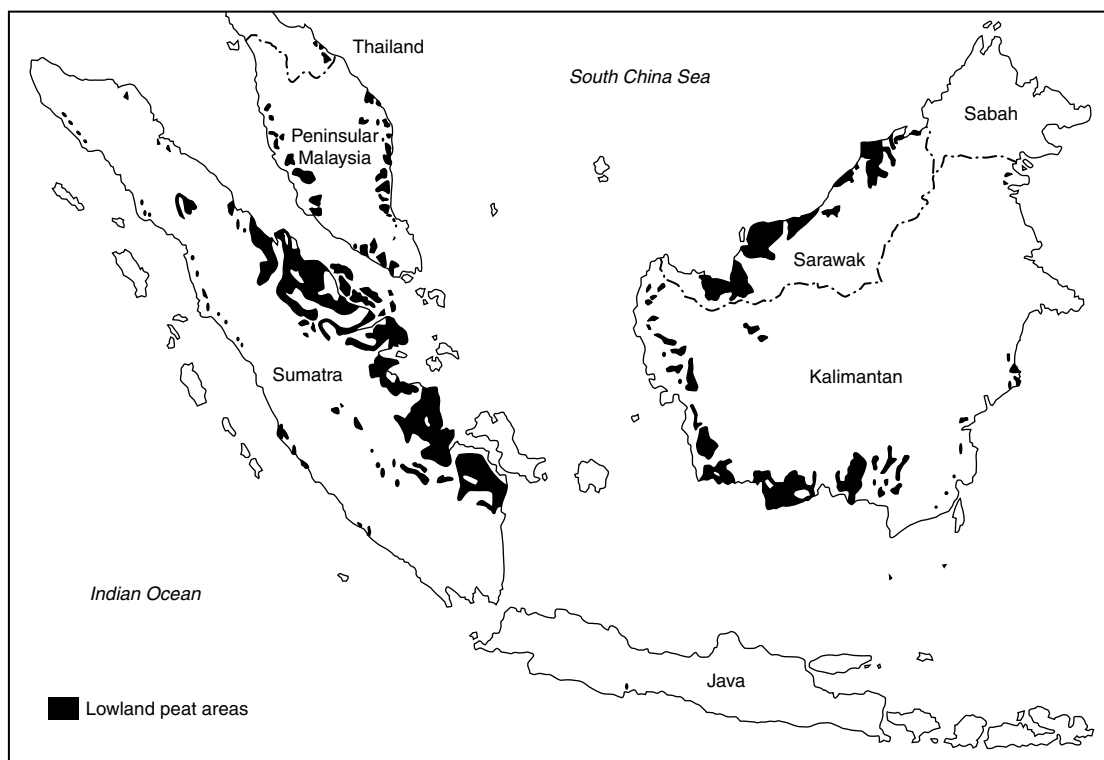


Fig. 3.7 Lowland peat areas in Malaysia and Indonesia (Fairhurst *et al.*, 1998).

11). Fairly shallow peats over clay, with about 100 cm of peat, have been used for palms for a considerable time, and their value is well defined. More recently, deep peat soils have been taken into use (Tayeb Dolmat *et al.*, 1996), on which there is less experience. There may be physical problems in draining the water in low-lying areas. The plantation will need a source of good water for its operations, as the local river or drainage water may be saline, or contain much humic acid. Depending on how the water table is controlled, the peat decomposes quite rapidly when exposed to air, and the level of the soil surface can therefore fall. This accentuates the leaning palm problem, and can make control of the water table even more difficult. If the drying is extreme, the soil becomes difficult to re-wet. The control of water is especially critical for those coastal peats that contain sulfides. Deep peat is very fluffy, and needs heavy compaction to give firm support for the palm; part of this normally occurs after drainage, when the peat compacts under its own weight.

The present view is that a peat with less than 1 m depth is very suitable for planting, 1–2 m is suitable and over 2 m is marginal (Fairhurst *et al.*, 1998). This gradual change in view has depended on better management techniques of water, nutrients and the soil. Better drainage, and fertiliser practices, compaction and hole-in-hole planting practices (see Section 8.3.6) have greatly improved the prospects, although Paramanathan (2000a) cautions that long-term experience is still lacking, and there may yet be unpleasant surprises.

The opening up of these soils raises many environmental problems. In the past many of these areas have been cleared by fire, after being logged over. Forest fires on peat spread to the peat itself, where they are very difficult to extinguish, and may continue to burn until the profile is wetted by rain (see Section 8.3.6). This occurs despite the Indonesian law that forbids burning in developing land, but that appears to be frequently ignored (Sargeant, 2001). It is suggested that this is damaging the reputation of the oil palm industry, which is otherwise environmentally friendly (see Section 15.3).

3.4.3.8 Hilly and sloping soils

Such soils have often been planted in the past, mostly using terracing or single-palm platforms, and acceptable yields have been obtained. However, there are serious dangers of erosion (Maene *et al.*, 1979; Hamel 1986), especially during planting, and for this reason the slope should preferably not be more than 12°, and certainly not more than 20° (Hartley, 1988; Goh and Chew, 2000;

Paramanathan, 2000a). There are often problems of access and of transfer of FFB to the factory. The problem now is that mechanisation is becoming essential in relatively high-wage countries such as Malaysia (see Section 8.3.5), where much of the remaining unplanted land is on slopes. Machinery access then becomes essential, and the plantation must be planned for this over one or more planting cycles of the palms (see Section 8.3.4). The problem is one of terrain rather than soil, except that on steep slopes the soil is very often shallow, and erosion may make it more so.

The rapid establishment of legume covers is essential. After this, oil palm plantations are relatively resistant to erosion, compared with almost all other forms of agricultural land use (Lim, 1990; Lavelle, 1994), and can support a large amount of soil fauna, which maintains soil structure. A monocrop such as oil palms, even with a legume cover, will normally have less soil biodiversity than natural forest, but may have a higher biomass of soil fauna (Lavelle, 1994; Khalid *et al.*, 1998).

3.4.3.9 Volcanic ash soils

These are adepts in Soil Taxonomy and andosols in the FAO–UNESCO (1990) system. They are not widely used for oil palm. The usual problems of phosphate deficiency are often encountered (Sanchez, 1976) and the very low density of the soil makes the palms prone to lean or fall. There are some peculiar aspects to the potassium nutrition and an apparent shortage of chlorine (see Section 11.4.5). However, many volcanic soils are well supplied with nutrients and can be planted very successfully.

3.4.3.10 Very weathered and leached soils

These include oxisols and some ultisols in Soil Taxonomy, and ferralsols and acrisols in the FAO–UNESCO system. These soils are very commonly used for oil palms. They are dominated by kaolinite, and by iron and aluminium oxides (Table 3.18). They appear to have a fine and well-aggregated structure, but this is so porous and lacking in expanding clay minerals that they can be prone to drought in dry spells. For the latter reason, they have very low exchange capacity, and some oxisols may even have a net positive charge on the mineral surfaces, so the soil adsorbs exchangeably more anions than cations. The high oxide content causes strong sorption of phosphate ions (Table 3.18). There is low pH and strong aluminium saturation. They therefore easily lose

Table 3.18 Phosphate sorption capacity of some common Malaysian soils, and contents of kaolinite, gibbsite (aluminium oxide) and ferric oxides

P sorption	Soil	Order	P fixed (mg/kg)	Kaolinite (%)	Gibbsite (%)	Ferric oxide (%)
Low	Marang	Ultisol	208	n.d.	–	0.30
	Lanas	Ultisol	247	5.61	–	0.67
	Rengam	Ultisol	308	8.68	0.69	1.31
	Tebok	Ultisol	383	11.84	–	0.29
	Serdang	Ultisol	396	13.03	0.26	0.93
	Tok Yong	Ultisol	450	16.87	3.24	2.96
Moderate	Harimau	Ultisol	568	16.02	1.02	3.30
	Jempol	Oxisol	571	4.25	–	1.30
	Bungor	Ultisol	663	9.05	–	2.18
	Lanchang	Ultisol	668	38.64	–	5.23
	Beserah	Ultisol	710	22.96	6.37	2.70
	Munchong	Oxisol	735	31.84	7.76	5.87
Strong	Sg. Mas	Oxisol	928	19.91	0.66	10.06
	Prang	Oxisol	985	40.22	4.06	4.89
	Segamat	Oxisol	1,084	33.87	–	7.4
	Kuantan	Oxisol	1,172	21.17	9.80	18.85

After Teo *et al.* (1998).

their exchangeable cations under heavy rainfall. Some may have plinthite gravel in the whole profile or in layers. These detrimental properties may not prevent successful palm cultivation, but they demand a high standard of care. Salako *et al.* (2001) investigated the effects of various fallow plant covers on the soil properties of a ‘degraded alfisol’, which would be rather similar to some of these soils. They determined that several years of fallow always improved the soil structure, using various measures, but that this improvement was fragile and readily lost when cropping started. *Pueraria phaseoloides* had a smaller effect than natural vegetation, but the effect of the latter was more rapidly lost. The structure of these soils is thus very dependent on recent treatment.

The ability of tropical soils to sorb phosphate strongly has been emphasised for a long time. Ultisols and oxisols in particular contain large amounts of iron and aluminium oxides, especially if plinthite is present. Data for common Malaysian soils, including Rengam and Munchong, are given in Table 3.19 (Teo *et al.*, 1998). The effects of increasing concentrations of ferric oxide, gibbsite (aluminium oxide) and kaolinite on the adsorption measurement are obvious. The sorption of phosphate is not a specifically unfavourable feature for oil palm, which has mycorrhizal roots (see Section 11.2.2), but phosphorus is an essential element, and on strongly sorbing soils large quantities of phosphate rock may

have to be applied, which slowly decomposes and fills the absorbing capacity. High rates of application, or placement of the fertiliser, are usually recommended on such soils (Vanlauwe *et al.*, 2001).

3.5 SOILS OF THE OIL PALM REGIONS

3.5.1 Soils of Asia

3.5.1.1 Malaysian soils

The oil palm areas in Malaysia are either on the ‘inland’ soils or the ‘coastal’ soils. The former include the Rengam series [kandiudult/kandiudox, with typic, aquic and plinthic suborders (Soil Taxonomy); rhodic nitisol (FAO–UNESCO)]. The saprolite (decaying rock) layer and the soil contain potassium-containing minerals. K-feldspar, mica and mica-smectite do not release potassium very rapidly, but there is a steady supply to the upper soil (Hamdan *et al.*, 1999). Jerengau series (typic acrodex) (geric ferralsol) and Tampin series (lithic hapludult) (haplic Acrisol) series derived from acid igneous rocks are also much used. On metamorphic rocks and sedimentary deposits a variety of other soils form, from the sandy loam Kedah series (lithic hapludult/dystric leptosol) to the heavy silt clays of the Batu Anam series, with a high but varying water table and occasional plinthite (laterite, ironstone). The Malacca (petroferic

haplodox/dystric leptosol) series has much larger, but varying amounts of plinthite, sometimes in large blocks, in a clay loam soil. The Kuantan series is derived from basalt. It is well supplied with plant nutrients, particularly phosphate (Table 3.19).

The coastal soils include the Selangor (Table 3.19) and the Bria series. The former are marine clay deposits, the latter river alluvium, formed on deposits along the coast of Malaysia. Both have high water tables, and drainage is a vital point in their use for oil palms. They have been drained for the cultivation of crops for a long time, and there is a view that they were at one time overdrained and suffered from dried-out profiles. The consensus is now to keep the water table at 80 cm (Chuah and Lim, 1989). Mostly they have clay textures with good structure. Further inland are the peat soils.

The soils of Sabah and Sarawak were surveyed and classified in different ways, so that there are difficulties in obtaining unified Malaysian soils maps (Paramanathan, 2000b) (Section 3.4.1.3). However, mapping and description have proceeded rapidly because of the development of plantations there. The sulfidic peats were discussed by Gopinathan and Joseph (1980), including all the early literature, and they suggested a more detailed classification of acid sulfate soils of South-east Asia. This was based on the depth at which sulfide first appeared, where the sulfide material lies and the speed at which it oxidises.

Much of the open land remaining for planting in South-east Asia is now peat. The largest areas are in western Malaysia and eastern Sumatra, and on the northern and southern coasts of Borneo (Fig. 3.7). If they are developed, there may be rapid shrinkage of up to 1–2 m in a few years (see Chapter 8), so that the surface of the peat may eventually lie very close to or below the water table. Peat has little mechanical strength unless it is compacted (see Section 8.3.6), and nutrition may be difficult.

Some general properties of soils in the oil palm areas of Malaysia and Indonesia are given in Table 3.20 (Foster, 1995), as there are some similarities, and to show the wide range that can be found.

3.5.1.2 Indonesian soils

The Indonesian system of classification is based essentially upon the Soil Taxonomy system, with the names often taken from the FAO–UNESCO (1990) system with phonetic transliteration. An English translation is available (Paramanathan, 1995).

Lubis and Adiwiganda (1996) listed the Indonesian oil palm soils in fertility groups. Thus, the high-fertility

group consists of eutric tropofluvents (a brown alluvial soil) only. The slightly high-fertility soils include aquic/typic hapludand (a greyish brown andosol) and typic dystropept (reddish or yellowish brown podsolc soil). The hapludand is a young volcanic soil, found both in lowlands and uplands. As usual, this soil is of high general fertility, but a high phosphate fixation is caused by allophane or imogolite aluminosilicate minerals. The dystropept is derived from volcanic material, and contains K-releasing micas. The moderately fertile group contains areic tropaquept (low humic gley) and typic hapludult (yellow–red podsolc). The former may contain some material typical of andosols. The latter contains much illite, which can lead to potassium fixation. The moderate to low fertility group contains topic ochraqults (grey hydromorphic soils) aeric topaquepts (brownish grey alluvial soils) and typic tropopsamments (grey–brown regosol). The first and second are alluvial soils with varying water tables and the third is a sandy soil in Sumatra.

The low-fertility soils are ultisols, peats and Tertiary sandy soils. The poorest group contains plinthite, and all are prone to erosion, compaction and leaching. The soils have been grouped by land suitability. The factors limiting yield on commercial estates in the west part of Indonesia (Sumatra, Lampung and west Kalimantan) were mainly climatic, with some soil factors (Purba and Lubis, 1993).

3.5.2 Soils of Africa

3.5.2.1 Nigerian soils

The Nigerian oil palm soils have been described by Omoti and Isenmila (pers. comm.). By far the greater part of the Nigerian palm belt, both wild and planted, is on the 'Acid Sands' soils. These are developed on Tertiary and Cretaceous sediments, and the most recent parts, on which most of the palms grow, are largely unconsolidated sandstones or 'Benin sands'. These soils were classified as 'fasc's' (Vine, 1956; Tinker and Ziboh, 1959a), which are accepted as equivalent to soil families in present terminology. Under the Soil Taxonomy system they are paleudults and dystropepts, and under the FAO–UNESCO (1990) system they are dystric nitosols and dystric cambisols (Ojanuga *et al.*, 1981). The soils were subdivided into series on the basis of differences of texture with depth (Vine, 1954), and have been redefined by Ogunkunle *et al.* (1999). Over the whole palm belt, the soil colour grades with

Table 3.19 Soil profile analyses for typical inland and coastal soils from Malaysia(a) *Inland soil basic igneous rock parent material*

Depth (cm)	0–8	8–30	30–61	61–91	91–122
Kuantan series (basalt derived)					
Clay (%)	63	70	71	69	67
Silt (%)	10	9	10	10	10
Sand (%)	27	21	19	21	23
C (%)	3.14	1.21	0.77	0.77	0.49
N (%)	0.15	0.04	0.04	0.03	0.03
pH	4.2	4.1	4.7	4.7	4.6
Exch. K (meq/100 g)	0.19	0.07	0.06	0.06	0.06
Exch. Ca (meq/100 g)	0.42	0.03	<0.05	<0.05	<0.05
Exch. Mg (meq/100 g)	0.74	0.20	0.16	<0.05	<0.05
CEC (meq/100 g)	20.2	11.5	10.1	9.2	8.2
P _i easily sol. in NaOH (ppm)	177	203	242	223	287
P _i conc. HCl sol. (ppm)	885	750	825	845	1,260

(b) *Inland soil. Acid igneous rock parent material*

Depth (cm)	0–8	8–30	30–61	61–91	91–122
Rengam series (granite derived)					
Clay (%)	43	46	58	65	66
Silt (%)	6	6	2	4	4
Sand (%)	51	48	40	31	30
C (%)	1.49	0.71	0.49	0.40	0.46
N (%)	0.16	0.11	0.07	0.06	0.06
pH	4.6	4.2	4.2	4.5	4.5
Exch. K (meq/100 g)	0.41	0.17	0.12	0.09	0.09
Exch. Ca (meq/100 g)	0.08	<0.05			
Exch. Mg (meq/100 g)	0.33	<0.05			
CEC (meq/100 g)	7.3	5.0	5.3	6.0	6.3
P _i easily sol. in NaOH (ppm)	39	22	19	19	18
P _i conc. HCl sol. (ppm)	161	113	121	114	124
Jerangau series (granodiorite)					
Clay (%)	36	50	57	59	57
Silt (%)	4	3	4	2	4
Sand (%)	60	47	41	39	39
C (%)	4.23	1.33	0.83	0.64	0.52
N (%)	0.21	0.09	0.06	0.05	0.05
pH	4.0	4.2	4.2	4.4	4.5
Exch. K (meq/100 g)	0.20	0.08	0.07	0.06	0.06
Exch. Ca (meq/100 g)	<0.05				
Exch. Mg (meq/100 g)	0.33	<0.05			
CEC (meq/100 g)	13.7	8.7	7.5	5.8	5.6
P _i easily sol. in NaOH (ppm)	72	51	48	60	29
P _i conc. HCl sol. (ppm)	211	221	224	239	232

(c) *Inland soil. Sedimentary rock parent material*

Depth (cm)	0–8	8–30	30–61	61–91	91–122
Serdang series (sandstone)					
Clay (%)	22	34	36	42	42
Silt (%)	2	2	2	2	2
Sand (%)	76	64	62	56	55
C (%)	1.27	0.52	0.40	0.27	0.30
N (%)	0.10	0.06	0.04	0.03	0.03

(Continued)

Table 3.19 (Continued)

Depth (cm)	0–8	8–30	30–61	61–91	91–122
pH	4.7	4.5	4.5	4.6	4.7
Exch. K (meq/100 g)	0.14	0.10	0.08	0.08	0.10
Exch. Ca (meq/100 g)	0.08	0.05	<0.05		
Exch. Mg (meq/100 g)	0.42	0.42	<0.05		
CEC (meq/100 g)	7.3	6.8	6.3	6.8	6.7
P _i easily sol. in NaOH (ppm)	37	38	39	39	54
P _i conc. HCl sol. (ppm)	62	75	88	97	105
Munchong series (shale)					
Clay (%)	63	69	71	70	73
Silt (%)	8	4	6	6	6
Sand (%)	29	27	23	24	21
C (%)	2.75	0.41	0.17	0.07	0.04
N (%)	0.26	0.11	0.09	0.07	0.04
pH	4.3	4.3	4.7	5.1	5.5
Exch. K (meq/100 g)	0.30	0.12	0.09	0.09	0.09
Exch. Ca (meq/100 g)	0.04	<0.05			
Exch. Mg (meq/100 g)	0.42	0.30	0.33	0.33	0.33
CEC (meq/100 g)	11.0	10.0	9.8	8.0	6.6
P _i easily sol. in NaOH (ppm)	32	18	15	14	11
P _i conc. HCl sol. (ppm)	92	92	76	81	–

(d) Coastal soil. Alluvium parent material

Depth (cm)	0–10	10–36	36–109
Briah series (river flood plain alluvium)			
Clay (%)	62	65	62
Silt (%)	35	33	31
Sand (%)	3	3	6
C (%)	3.34	0.32	0.23
N (%)	0.28	0.09	0.06
pH	4.5	4.5	4.4
Exch. K (meq/100 g)	0.52	0.14	0.23
Exch. Ca (meq/100 g)	1.43	0.50	1.18
Exch. Mg (meq/100 g)	2.20	1.94	5.56
CEC (meq/100 g)	25.8	21.0	20.0
P _i easily sol. in NaOH (ppm)	79	73	77
P _i conc. HCl sol. (ppm)	225	115	100

Depth (cm)	0–15	15–30	30–61	61–104	104–135
Selangor series (marine clay)					
Clay (%)	80	79	81	70	68
Silt (%)	18	17	17	18	20
Sand (%)	2	4	2	12	12
C (%)	1.31	1.04	0.82	1.01	1.44
N(%)	0.20	0.18	0.11	0.11	0.09
pH	4.7	4.3	4.3	5.4	7.7
Exch. K (meq/100 g)	1.57	0.93	0.78	0.80	2.34
Exch. Ca (meq/100 g)	4.8	3.9	5.1	8.1	10.7
Exch. Mg (meq/100 g)	14.2	10.0	10.7	13.8	17.2
CEC (meq/100 g)	32.5	32.5	30.0	30.9	52.0
P _i easily sol. in NaOH (ppm)	65	84	125	128	42
P _i conc. HCl sol. (ppm)	226	207	244	322	335

After Hartley (1998).

Note: 1 meq/100 g = 1 cmol/kg for K, and 0.5 cmol/kg for Ca and Mg. CEC is given as cmol electric charge/kg soil, equal to meq/100 g.

Table 3.20 Comparison of typical soil analysis data (0–20 cm depth) taken from experimental sites in four very different soils in South-east Asian soil regions

Region and soil	C (%)	N (%)	pH	Exchangeable cations (meq/100 g)			Total	K/CEC
				Ca	Mg	K		
Malaysian inland	1.2	0.12	4.33	0.88	0.43	0.33	1.64	0.20
Papua New Guinea volcanic	2.2	0.22	6.10	8.10	1.55	0.24	9.89	0.024
Malaysian coastal	1.5	0.15	4.07	2.04	2.73	1.82	6.59	0.27
North Sumatran volcanic	0.6	0.21	4.80	0.98	0.72	0.42	2.12	0.20

Foster (1995).

CEC: cation exchange capacity.

increasing rainfall from deep red in the north-west to yellow-brown in the south-east, as the pH decreases from 5–6 to 4–4.5 (Table 3.21). Near Nsukka there are serious instances of gully erosion of these soils (Gobin *et al.*, 1999), but normally there is only surface wash where the vegetation cover is sparse. The landforms largely consist of plateaux between deeply incised river valleys. The slopes of these may have plinthite outcrops.

Around the 'Acid Sands' are Basement Complex rocks, and some of these soils carry oil palms, including plantations in what was considered to be the cocoa area of western Nigeria, and intercropping with cocoa may be used. However, the rainfall on most of the Basement Complex areas, except those in the east, is only marginal for oil palm, at below 1500 mm. Most of the soils are alfisols, inceptisols and entisols; under the FAO–UNESCO (1990) system they are mainly luvisols. They are thus more chemically fertile than the Acid Sands soils (Table 3.21), but they are often stony and steep, with very variable rooting depth, even where the rainfall is adequate.

The Acid Sands adjoin alluvial soils of the Niger delta to the south. Nearly all have high water tables, and hydromorphic indications occur even in the A horizon of soils otherwise classed as Ultisols. There are vast areas of these soils, and given good drainage and fertility management they should give good oil palm yields.

There is obviously considerable potential to use all these soils for oil palms, the main problem being the seasonal climate. Except in the south-east of the country, the dry season is of such length that the available water in the soils is a dominant factor. The possibility of rooting to a depth of several metres in clayey sand/sandy clay is an advantage the Acid Sands soils under lower rainfalls, but it does not fully compensate for the seasonal climate.

3.5.2.2 Other West African soils

The regular oil palm soils in Benin, Ghana, Ivory Coast and Sierra Leone are all developed from Tertiary sand-stone deposits fairly near to the coast, and are basically similar to the Acid Sands of Nigeria. In the Ivory Coast the sandy soils are particularly fertile, and are contiguous to the sandy soils in Ghana (Caliman *et al.*, 1994). However, the rainfall distribution is such that some Basement Complex soils are also used. A typical profile from this area is shown in Table 3.21. Seasonal drought is a particular problem, and much effort has been put into ameliorating the effects of the dry season, particularly in Benin (Cornaire *et al.*, 1994; Nouy *et al.*, 1999). These authors listed four methods for reducing the effects: bare soils cropping, castration to reduce bunch demand, irrigation and reducing planting density. All of these have drawbacks which make them non-viable in many sites. Castration to reduce bunch photosynthate demand is possible up to 36 months from planting, and IRHO work has shown that this improves drought tolerance (see Section 4.3.7.3). The fourth method might also be used generally in the West African circumstances.

The sandy ferrallitic soils described above appear to suffer from compaction in the Ivory Coast, where Caliman *et al.* (1988) showed that subsoiling before replanting with oil palms produced a yield response. This seems to be a unique case of deep soil cultivation for oil palm culture.

3.5.2.3 Soils of the Democratic Republic of the Congo

The soils of the northern part have been described as hygro-kaolinitic ferralsols (FAO–UNESCO, 1990), probably equivalent to ultisols. These are formed from

Table 3.21 Soil profile analyses from typical African soils on Nigerian Acid Sands soils, and Basement Complex rocks, and a Congo ferralsol

(a) Basement Complex soil. Schist and granite parent material with drift

Depth (cm)	0–5	5–30	30–58	58–99	99–152	152–203
Stones and gravel (%)	17	23	50	44	28	21
Clay (%)	7	15	27	23	43	42
Silt (%)	3	5	3	7	6	7
Fine and coarse sand (%)	90	80	70	70	51	51
C (%)	1.7	0.9	0.7	0.4	0.4	0.4
N (%)	0.08	0.05	0.04	0.03	0.03	0.03
pH	3.6	5.2	5.4	5.5	5.3	5.5
Exch. K (meq per 100 g)	0.20	0.10	0.18	0.06	0.10	0.09
Exch. Na (meq per 100 g)	0.40	0.30	0.35	0.28	0.52	0.45
Exch. Ca (meq per 100 g)	0.96	0.20	0.16	0.06	0.24	0.22
Exch. Mg (meq per 100 g)	0.48	0.16	0.24	0.12	0.24	0.18
Total exch. cations (meq per 100 g)	2.04	0.76	0.93	0.52	0.10	0.94
Exch. capacity (meq per 100 g)	4.9	4.6	5.5	4.3	7.0	6.9

After: Tinker (1962).

(b) Soil on Nigeria Acid Sands Calabar series (unconsolidated sands and clays)

Horizon	A1	A2	B21	B22	B23	B24	B25
Depth (cm)	0–12	12–26	26–68	68–95	95–118	118–150	150–190
pH	4.2	4.0	4.0	4.2	4.1	4.0	4.0
Ca (meq/100g soil)	0.33	0.25	0.25	0.20	0.15	0.20	0.20
Mg (meq/100g soil)	0.13	0.04	0.04	0.05	0.04	0.04	0.04
K (meq/100g soil)	0.18	0.06	0.06	0.05	0.06	0.05	0.05
Na (meq/100g soil)	0.11	0.12	0.14	0.12	0.12	0.10	0.10
CEC (meq/100g soil)	13.5	9.7	8.4	8.2	8.5	8.3	8.0
C (%)	1.42	0.55	0.40	0.17	0.15	0.15	0.07
N (%)	0.09*	0.06	0.05	0.04			
Avail. P (ppm)	16.4	–	–	–	–	–	–
Sand (%)	77	78	70	70	70	70	72
Silt (%)	9	6	6	6	3	3	4
Clay (%)	14	16	24	24	27	27	24

Sources: Ojanuaga *et al.* (1981); SOCFINCO (1975), *Tinker and Ziboh (1959), Enwezor *et al.* (1981).

(c) Profile analysis: Yangambi latosol (ferralsol) Congo Forest. Annual rainfall 1800 mm

Horizon	A1–A3	B1	B2	C
Depth (cm)	20	45	65	120
Clay (%)	26.3	30.0	38.7	35.6
Silt (%)	2.1	2.0	2.1	1.7
Sand (%)	71.6	68.0	59.2	62.7
C (%)	1.2	0.5	0.4	0.3
N (%)	0.10	0.6	0.04	0.03
pH	4.6	4.5	4.4	4.5
Exch. Ca (meq per 100 g)	1.2	0.6	0.4	0.4
Exch. capacity (meq per 100 g)	3.5	4.5	4.6	4.3

Note: No data for exchangeable K or Mg are given for this profile. In a similar profile analysis by Kellogg and Davol exch. K was 0.2–0.3 and exch. Mg 0.1 meq per 100 g at all positions in the profile down to 1800 mm.

Source: Sys (1960).

a thick layer of wind-borne material, as are most of the oil palm soils of the country. The terrain is undulating, with very sandy soils in the valleys resulting from erosion, and more clayey soils on the upper slopes. In southern Congo the very sandy oil palm soils of the groves are called arenoferral soils. Interspersed with these are more fertile red soils developed from sedimentary rock. No recent work appears to have been done on the soils of this country.

3.5.3 Soils of America

The oil palm can be grown from the south part of Mexico to Bolivia (Lauzeral, 1980). The relation of the FFB yield with the water deficit for three classes of soils is in Fig. 3.8 (Lauzeral, 1980). The three classes are: (1) exceptional soils: volcanic ash soils (andosols) of Ecuador; alluvial soils on plains of Colombia; (2) moderately good soils: old alluvial soils of Peru; clay soils of Panama; and (3) poorer soils: Brazilian vertisols; sandy soils of Mexico. This range of soils is very wide, covering all textures from heavy clay sand or volcanic ash. Sets of analysis of most of these are presented in Table 3.22. The pH values tend to be higher than in the oil palm soils of Asia and Africa, in soils of volcanic origin or in recent alluvium. These soils can be divided up into topographical situations (Lauzeral, 1980).

- River valleys, and their flood plains and terraces. These are defined by the extent of flooding. The value of these soils depends on their good structure and texture, although they usually have high water tables and signs of hydromorphism, and there is much swampland. Such soils are found on the upper Amazon in Peru, and around the Magdalena River in Colombia.
- Alluvial plains around mountain chains have a wide mixture of soils, which are often stratified and are prone to inundation. Their chemical fertility is good but there is often a deficiency of potassium
- Alluvial plains of the coasts are found on both the Atlantic and Pacific coasts. The sandy soils are short of water, hence their use depends on rainfall, the water table or irrigation. The clay soils usually contain montmorillonite clays and are very heavy in the wet season. They can be used with appropriate fertilisation.
- Soils developed on sedimentary formations. On the Amazon, these are often heavily leached ultisols, deep, with low pH, sometimes with plinthite. Their chemical fertility is poor, especially in phosphorus,

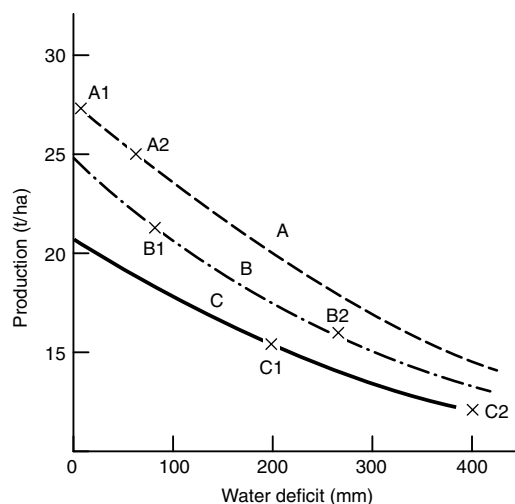


Fig. 3.8 Yield of FFB in relation to water deficit (IRHO) on three groupings of soils by yield level, with A the largest yields A1: volcanic ash soils of Ecuador; A2: alluvial soils of Colombia; B1: old alluvium in Peru; B2: clay soils of Panama; C1: vertisols in Brazil; C2: sandy soils in Mexico. (After Lauzeral, 1980.)

but otherwise they are very favourable for oil palm cultivation if they are properly fertilised. Lauzeral (1980) noted four different types of relief within these areas, the most extensive being the peneplains in the interior of the Amazon. A set of soil analyses from a clay soil near Manaus in the Amazon is shown in Table 3.23, where Rodrigues *et al.* (1997) reported a series of fertiliser experiments showing a frequent need for phosphate.

- Soils of recent volcanic origin. These are mainly found in Ecuador and are now andosols. They are chemically very rich and require almost no fertilisation. They have a large water-holding capacity, and their only problem is that they are mechanically weak, so that machinery has to be used with care.

In general, the fertility of the soils is good, and the need for fertilisation is only moderate, a result of the recent volcanic activity or the erosion in the Andes that deposits nutrients over most of the flood plains. This accounts for the fertility of the soils where oil palms are being developed (Hartley, 1988).

In Costa Rica there are two main areas for oil palm planting, the central Pacific region (Quepos) and the south Pacific region (Table 3.24). The latter consists of an area with alluvial calcareous soils and one with

Table 3.22 Soil analyses (topsoil^a and subsoil^b) of soils from South and Central America that carry oil palms

Soil classification and place of origin		Texture analysis %					Organic matter		Exchangeable cations				CEC	Saturation (%)	pH	Total Phosphate (mg/kg)
		Clay	Silt	Sand			C (%)	N (%)	(meq/100 g)							
				Very fine	Fine	Coarse			Ca	Mg	K	Na				
Vertisol	a	55	22	20	2	1	3.5	3.4	30.0	13.0	0.95	0.30	–	–	5.5	220
Val d'Iguape Bahia Plantation, Brazil	b	70	15	13	1	1	1.5	1.2	27.0	16.0	0.70	0.60	–	–	–	–
Recent alluvial soil	a	16	27	17	37	3	0.2	0.3	13.9	5.9	0.15	0.2	20.6	98	6.4	1,220
San Alberto Plantation, Colombia	b	4	23	19	45	9	0.1	0.03	10.1	7.5	0.09	0.4	18.8	98	6.8	1,660
Old alluvial soil	a	36	26	13	6	19	1.6	1.5	1.1	0.2	0.40	0.02	7.4	24	4.8	293
Tocache Plantation, Peru	b	37	27	14	5	17	0.8	0.9	0.3	0.1	0.20	0.02	6.1	9	4.4	202
Red clayey hill soils																
Castillo Plantation, Nicaragua	a	50	36	–	14	–	3.6	–	5.0	4.1	0.25	0.7	30.1	33	4.5	–
	b	69	92	–	9	–	1.2	–	2.5	2.3	0.14	0.6	19.5	28	4.5	–
Volcanic rock soils	a	28	24	16	30	–	–	–	–	3.3	3.4	0.5	–	–	6.8	420
Quininde Plantation, Ecuador	b	18	21	20	38	3	1.3	1.9	5.5	2.4	1.6	0.5	13.7	73	6.4	280
Volcanic ash soils	a	18	17	32	33	1	7.8	1.8	4.0	0.9	0.23	0.6	26.1	22	5.3	1,800
Lago Agrio Plantation, Ecuador	b	43	21	21	13	2	1.8	1.03	4.4	2.3	0.25	0.4	25.8	28	5.9	1,200
Latosol	a	16	25	18	31	10	2.1	1.9	0.07	0.07	0.06	0.01	9.0	2.3	5.0	75
Téf�, Brazil	b	21	25	19	28	7	1.0	1.5	0.1	0.03	0.02	0.01	7.1	2.2	4.9	50

After Lauzeral (1980).

a: 0–20 cm (topsoil); b: 30–50 cm (subsoil).

CEC: cation exchange capacity.

Table 3.23 Composition of clay soil on an experimental site, Manaus region, Brazil

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Org. C (%)	Tot. N (%)	Tot. P (µg/g)	Avail. P ^a (µg/g)	Exchangeable cations (meq/100g)		
								Ca	Mg	K
0–20	74.6	9.7	15.7	2.65	0.27	157	8	1.58	0.39	0.11
20–30	85.4	5.5	9.1	1.32	0.14	116	3	0.38	0.10	0.04

After Rodrigues *et al.* (1997). ^aBrays No. 2 method

Table 3.24 Typical composition of soils in the two regions of Costa Rica carrying oil palms: the Coto region is far to the south and the Quepos zone is on the Pacific coast

Depth (cm)	Texture			OM %	pH (H ₂ O)	Exchangeable cations (meq/100 g)			CEC (meq/100 g)
	Sand	Silt	Clay			Ca	Mg	K	
Soils of Coto									
0–30	42	25	33	1.83	5.7	30.9	8.1	0.36	43.2
30–70	28	41	31	0.52	5.8	33.7	8.6	0.28	46.4
70–100	30	43	27	0.56	6.0	40.3	9.1	0.34	51.4
100–130	30	47	23	0.42	6.3	41.8	8.3	0.20	52.7
130–150	38	37	25	0.50	6.7	43.3	8.2	0.30	53.1
Soils of Quepos									
0–20	2	55	43	3.22	5.7	15.1	4.2	0.08	30.7
20–55	1	76	23	0.47	6.3	13.0	3.7	0.04	22.9
55–73	3	44	53	tr	6.1	16.9	5.7	0.02	29.4
73–90	2	53	45	tr	6.0	18.2	6.2	0.17	27.2
90–120	2	39	59	tr	6.2	20.7	6.7	0.21	33.7
120–150	32	41	27	tr	6.2	18.1	6.3	0.31	25.7

Duran, Alvarado and Peralta (pers. comm., 2001).

CEC: cation exchange capacity; tr: trace; OM: organic matter.

alluvial volcanic soils. The Quepos region consists of clay soils containing smectites.

Munevar (1998) described the great diversity of soils in Colombia, with entisols and inceptisols, and discussed the problems of planting oil palms on these soils. Wilson-Bibiano *et al.* (2001) have given details of the soils used for oil palm cultivation in Mexico.

3.6 LAND CLASSIFICATION

The combination of climate, soil and socioeconomic factors is the subject of land classification. This is so closely connected with site selection that it is covered in Chapter 8.

Chapter 4

Growth, Flowering and Yield

Growth of all green plants involves the fixation of carbon dioxide, by photosynthesis, to form the 'dry matter' of plant tissues. The energy supply for photosynthesis comes from solar radiation. The energy absorbed by the leaves is used, in the chloroplasts, to convert carbon dioxide, taken up by the leaves through the stomata, and water, taken up from the soil by the roots, to carbohydrate (sugar). Key factors in understanding plant growth are, therefore:

- the total amount of solar energy available
- the extent to which this energy is intercepted and absorbed by the leaves
- the efficiency of conversion into chemical energy of carbohydrate.

In the first section of this chapter we describe how growth of oil palms has been measured and analysed. Partitioning of dry matter between vegetative growth and yield of fruit bunches is reviewed in the second section. As will be seen in this chapter, and in Chapter 5, the analysis of dry matter production and partitioning has been particularly helpful in defining objectives in oil palm breeding. In the third section, the effects of environmental and management factors on dry matter production are discussed. Flowering and the yield components, bunch number and bunch weight, are covered in the fourth section. In the final part of the chapter we review the interactions between growth, flowering and the environment which determine the yield of bunches and of palm oil and kernels, and the subjects of yield forecasting and crop modelling.

4.1 ANALYSIS OF PLANT GROWTH

4.1.1 Background

4.1.1.1 History of plant growth analysis

The idea of plant growth analysis developed in the first half of the twentieth century. Early work involved the use of mathematical growth functions to describe plant weights and leaf areas, and the calculation of parameters

such as relative growth rate (RGR), net assimilation rate (NAR) and crop growth rate (CGR). The physiological basis of RGR is easily understood: the amount of photosynthesis, and hence growth of a plant, depends on the size of the plant, in particular the leaf area. Thus, the larger the plant, the faster the growth rate. For an isolated plant, without competition from others, growth is often more or less exponential, with the increase in weight per unit weight already present being fairly constant; this is the RGR. Leaf area ratio (LAR) is the ratio of leaf area (usually that of one surface only) to plant weight, and NAR is the rate of increase in dry weight per unit leaf area. Thus:

$$\text{RGR} = \text{LAR} \times \text{NAR} \quad (4.1)$$

These parameters have been estimated for nursery oil palms (Rees and Chapas, 1963a; Rees, 1963e), but in field-planted palms they are of little value. Once the crop canopy closes, interplant competition starts to limit growth, which becomes linear rather than exponential. This means that growth per unit dry weight present is no longer constant, so at this point RGR is no longer a useful concept. Goudriaan and Monteith (1990) developed an 'expolinear' growth equation, to describe the transition from exponential to linear growth, and showed that this could be fitted to oil palm growth and yield data, with the transition occurring roughly 3 years after field planting.

In mature palms, CGR, the rate of dry matter production per unit area of land, is a more useful measure than RGR. CGR can be broken down into leaf area index (L , the leaf area per unit area of land) and NAR:

$$\text{CGR} = L \times \text{NAR} \quad (4.2)$$

These parameters have also been estimated for oil palms (Rees, 1962a; Rees and Tinker, 1963; Corley *et al.*, 1971a). NAR presents problems, because it is a derived parameter, not a direct measure of the rate of photosynthesis. If CGR is measured or estimated from plant dry weights, and L can be measured, then:

$$\text{NAR} = \text{CGR}/L \quad (4.3)$$

In some circumstances L can be increased without changing CGR; for example, stopping pruning in oil palms adds heavily shaded, old fronds, which photosynthesise very little. The calculated value of NAR is then reduced, although the total amount of photosynthesis of the canopy, and CGR, may be almost unchanged.

4.1.1.2 Modern concepts

Monteith (1977) introduced the concept of 'resource capture', considering plant growth in terms of the interception and use of solar energy, and partitioning of dry matter. The basic equation is:

$$Y = S \cdot f \cdot e \cdot H \quad (4.4)$$

where Y is yield of harvested product (t/ha or g/m²), S is incident solar radiation (MJ/m²), f is the fraction of the radiation absorbed by the foliage, e is the photosynthetic conversion coefficient or radiation use efficiency (g/MJ), and H is the partitioning coefficient or harvest index: the fraction of total dry matter allocated to the harvested product. Interception of radiation depends on leaf area index, but the relationship is non-linear, and the use of f rather than L , and e rather than NAR, removes some of the distortions that can occur with Equation 4.3 (but see Section 4.1.4.3). With annual crops, e often remains constant over quite long periods. Monteith (1977) demonstrated that e should, theoretically, be directly related to the rate of photosynthesis. The first analysis of oil palm growth in these terms was made by Squire (1983, 1986).

Another frequently mentioned concept is that of source and sink. The source of assimilates (carbohydrate) is the photosynthetic organs, usually the leaves. Sinks are the growing organs that use assimilates (roots, fruits, apical meristems). Evans (1993) pointed out that the concept of sources and sinks is an oversimplification; sinks can become sources (e.g. growing leaves as they mature), while some organs may be both source and sink. The development of sinks may be controlled by source activity (assimilate supply), but source activity (photosynthetic rate) may also be regulated by sink demand. Nonetheless, to help to decide which selection criteria to concentrate on in a breeding programme, it is sometimes useful to ask the question: is yield of a crop source limited or sink limited? This is discussed further in Section 4.2.2.

4.1.1.3 Factors limiting growth

The key resources for plant growth are light, carbon dioxide, water and nutrients. Equation 4.4 implies that

yield depends on radiation level; f , e and H are under some degree of control by plantation managers, agronomists and plant breeders, with only S outside their control. In practice, though, water supply, nutrient supply, and pest and disease damage may all limit growth and yield at times. As discussed below, some of these effects, such as defoliation by pests, are easily understood in terms of Equation 4.4. Other aspects, such as the interaction between radiation and humidity in their effects on photosynthesis, are more complex (Section 4.3.3.2).

Water: Water is essential for plant growth; many plant tissues are comprised of over 80% water. Through photosynthesis, water is combined with carbon dioxide to form carbohydrates, releasing oxygen. However, only a small fraction (less than 5%) of the water taken up is retained by the plant; most passes through the plant, in the xylem vessels, and is evaporated through the stomata. Transpiration is an unavoidable consequence of open stomata, through which carbon dioxide is taken in, but the transpiration stream also serves two useful purposes: mineral nutrients are taken up from the soil and transported throughout the plant, in solution, while the cooling effect of evaporation from the leaf surface maintains leaf temperature close to air temperature. Most plants respond to water shortage by closure of the stomata; this limits water loss and prevents or reduces tissue desiccation, but also restricts carbon dioxide uptake for photosynthesis. Lack of evaporative cooling may cause a rise in leaf temperature, sometimes to damaging levels.

Nutrients: Mineral nutrients, taken up from the soil, play a variety of roles in plant growth. The essential elements are defined and listed in Section 11.1.2; without adequate supplies of all of these, the normal physiological functioning of the plant will be restricted or prevented. For example, nitrogen is an essential component of all proteins. As enzymes are proteins, and most biochemical reactions in the plant are catalysed by enzymes, nitrogen plays an essential role in almost all physiological processes. Some of the effects of nutrients on oil palm growth are discussed in very general terms in Section 4.3.2.

Temperature: Plant growth may be limited by either low or high temperature. As temperature falls, growth rates diminish, and for many plants, particularly in temperate climates, low temperature is the main limiting factor for growth. Where oil palms are grown outside the latitudinal range discussed in Section 3.2.1, low night, or winter, temperatures may become restrictive, but in the main growing areas temperatures are relatively uniform throughout the year, rarely falling below

18–20°C, and low temperature is not a limitation. High leaf temperatures, particularly during periods of inadequate water supply, are a more important limiting factor for oil palm growth (Section 4.3.4).

Pests and diseases: These can affect yield in many different ways, but in physiological terms leaf-eating pests (caterpillars, in particular) may cause significant reductions in leaf area, and hence in light interception, while leaf diseases may reduce the photosynthetic rate. In immature (non-fruiting) palms, though, leaf damage by pests may have very little effect on subsequent yield, for reasons discussed further below (Section 4.2.2.1). Stem and root diseases may restrict water uptake by the palm, and the early symptoms of some of these disease are very similar to those of drought (Chapter 12).

4.1.2 Dry matter production

In this section, work on total dry matter production by oil palms is reviewed. The component processes, as specified by Equation 4.4, are discussed in subsequent sections.

4.1.2.1 Early work on oil palm

Most plant growth analysis has involved destructive measurements of dry weights, and some destructive studies have been done with oil palm. For the purpose of such growth studies, dry matter production by the palm over a given period may conveniently be divided into:

- new (open) leaves produced, comprising leaflets, rachises and petioles
- increase in trunk dry weight
- increase in weight of unopened leaves and growing point

- weight of male inflorescences produced
- weight of fruit bunches harvested
- increase in root dry weight
- weight of old roots replaced by new roots (root turnover).

Measurements of all these components except, in most studies, the last, have been made for oil palms of different ages in both West Africa and Malaysia, and rates of dry matter production have been estimated from the data (Rees, 1962a; Rees and Tinker, 1963; Ng *et al.*, 1968; Corley *et al.*, 1971a; Dufrene, 1989; Henson, 1995a; Lamade and Setyo, 1996a). Some of the results obtained are compared in Table 4.1. Rees (1962a) showed that the oil palm had a fairly high rate of dry matter production, and that this was mainly due to a high 'leaf area duration': complete ground cover throughout the year resulted in high light interception, and hence high total dry matter production, despite a relatively low NAR compared with annual crops. In terms of Equation 4.4, f is large, but e is lower than in annuals.

Table 4.1 shows that Ng *et al.* (1968) found higher figures for trunk dry matter increment than others, perhaps because they included the attached leaf bases with the trunk. Dufrene (1989) estimated total dry matter incorporated in roots, including replacement of old roots by new, whereas the other studies simply measured the net increase in total root weight. Apart from these differences, the amounts of dry matter in vegetative growth (VDM) were quite similar in Malaysia and in Africa, in contrast to yields, which were much higher in Malaysia. The similarity in VDM between Malaysia and Nigeria led Corley *et al.* (1971a) to hypothesise that vegetative growth might take priority when assimilate supplies were limiting (as in Nigeria with a long dry season). Subsequent work confirmed that

Table 4.1 Dry matter production in Malaysia and west Africa

Location	Palm age (years)	Palms/ha	Annual dry matter production (t/ha per year)								Ref. ^b
			Leaves	Trunk	Leaves + trunk	Roots ^a	Total vegetative	Male flowers	Bunches	Total	
Nigeria	7–22	148	10.0	3.2	13.2	1.1	14.3	–	4.8	19.1	1
Malaysia	8–15	122	8.6	7.0	15.6	0.5	16.1	0.3	14.0	30.4	2
Malaysia	6–18	122	13.8	2.2	16.0	0.4	16.4	0.7	12.6	29.7	3
Ivory Coast	10	143	10.9	2.1	13.0	11.5	24.5	0.8	8.8	34.1	4

^aFigures for roots represent net annual increase in total dry weight only, except for Ivory Coast, where replacement was also estimated.

^b1: Rees and Tinker (1963); 2: Ng *et al.* (1968); 3: Corley *et al.* (1971a); 4: Dufrene (1989).

this 'overflow model', which implies source limitation of yield, generally provides a reasonable fit to data (but see Section 4.2.2).

Some attempts have been made to estimate dry matter incorporated in the root system, including the replacement of old roots by new; these are discussed in Section 4.2.1.4.

4.1.2.2 Standing biomass

The term standing biomass is used to describe the total dry weight of a stand of plants in the field; this may have accumulated over many years in a perennial crop. The studies of oil palm dry matter production already mentioned produced estimates of standing biomass, which are summarised in Table 4.2. The main above-ground biomass accumulation occurs in the trunk, with 40 t dry matter per hectare or more in palms older than 20 years. It is not always clear, however, whether trunk biomass includes attached leaf bases; according to Henson (1995a) the biomass of leaf bases was

approximately equal to trunk biomass in 10-year-old palms. For palms older than about 10 years the weight of leaves is fairly constant: as new leaves open, old leaves die or are pruned off. The exception is the very vigorous Bah Jambi material studied by Lamade and Setiyo (1996a); both leaf and trunk biomass were nearly double that for other material at the same age.

4.1.2.3 Root biomass

Biomass of the root system can be estimated by digging up sample volumes of soil. Sampling errors must be large, but there are considerable differences between the reported figures for root biomass. Biomass may be greater in the dry climates of West Africa than in the Far East (Table 4.2), when plantings of similar age are compared. Dufrene (1989) found a total root biomass of 31.5 t/ha for 10-year-old palms in Ivory Coast, whereas Lamade and Setiyo (1996a) found only 14.1 t/ha for one family and 9.7 t/ha for another in Indonesia. Rees and Tinker (1963) found 16.4 t/ha for 17-year-old

Table 4.2 Oil palm biomass

Location	Palm age (years)	Palms/ha	Total standing biomass (t/ha)						Ref. ^a
			Leaves	Trunk	Roots	Total vegetative	Inflorescences	Total	
Nigeria	7	128	8.6	11.1	—	—	4.9	—	1
Nigeria	10	128	11.6	22.6	—	—	3.6	—	1
Ivory Coast	13	143	20.0	21.8	31.5	73.2	4.5	78.7	2
Nigeria	14	128	11.0	31.1	—	—	2.3	—	1
Nigeria	17	128	12.2	37.2	16.4	65.8	2.1	67.9	1
Nigeria	20	128	19.2	57.3	—	—	2.9	—	1
Nigeria	22	128	14.3	51.2	—	—	2.8	—	1
Mean			13.8	28.9	24.0				
Malaysia	1.5	148	8.0	1.1	1.3	10.4	—	—	3
Malaysia	2.5	148	19.6	2.9	2.4	24.9	—	—	3
Malaysia	4.5	122	12.7	6.0	4.4	23.2	—	—	3
Malaysia	6.5	122	14.4	10.7	5.0	30.1	—	—	3
Malaysia	8.5	122	12.2	13.7	5.4	31.3	—	—	3
Indonesia, LM	8	130	25.5	21.2	14.1	60.8	—	—	4
Indonesia, BJ	8	130	44.4	39.3	9.7	93.4	—	—	4
Malaysia	10.5	122	19.7	19.0	6.0	44.7	—	—	3
Malaysia	14.5	122	20.5	29.8	8.4	58.7	—	—	3
Malaysia	17.5	122	17.1	36.9	7.5	61.5	—	—	3
Malaysia	27.5	122	14.1	37.7	16.0	67.8	—	—	3
Mean, 6.5 years onwards			21.0	26.0	9.0				

All data are from direct (destructive) measurements of dry weight.

LM: Deli × La Mé; BJ: 'local Bah Jambi'.

^a1: Rees and Tinker (1963); 2: Dufrene (1989); 3: Corley *et al.* (1971a); 4: Lamade and Setiyo (1996a).

palms in Nigeria, while Corley *et al.* (1971a) found only 7.5 t/ha at the same age in Malaysia.

Tailliez (1971) found a greater root biomass on colluvial than on alluvial soils. Tan (1979) found a biomass of 6 t/ha on a concretionary soil, but 12 t/ha on a non-concretionary soil; he implied that above-ground growth was better on the latter soil, but gave no data. Henson and Chai (1997) found higher biomass on a coastal alluvial soil (15.9 t/ha at 10 years) than on inland soils (7.0–10.8 t/ha). Despite the difficulties of measurement, therefore, it seems clear that there are differences between soil types.

In the early years, root biomass increases with palm age, but it is not clear whether this continues beyond about 8–10 years, or whether, as with leaf biomass, a more or less constant level is maintained. The data of Corley *et al.* (1971a) showed no trend between 10 and 17 years, but a much greater biomass in 27-year-old palms. Whether or not biomass is constant, there will still be carbon allocated to root turnover in older palms (Section 4.2.1.4).

4.1.3 Non-destructive methods of measurement

For obvious reasons, destructive methods cannot be widely employed with a perennial crop, but Hardon *et al.* (1969) and Corley *et al.* (1971b) evolved non-destructive methods of estimating leaf area and annual dry matter production. These methods, based on correlations between dry weights and simple measurements, are cheaper and quicker than destructive analyses, can be repeated on the same palms at different times, and can be used on valuable breeding material where destructive work would be unacceptable. Following the introduction of these methods, growth analysis has been extensively used in comparisons of progenies, environments and agronomic treatments, and has greatly improved the understanding of yield and the limitations to it.

The non-destructive methods (see Box 4.1) only cover weights of leaves, trunk and bunches, but Corley *et al.* (1971a) found that these organs constituted over 96% of total annual above-ground dry matter

Box 4.1 Method for estimating oil palm dry matter production

Non-destructive methods have been developed to estimate dry weights of leaves and trunk and leaf area of oil palms (Hardon *et al.*, 1969; Corley *et al.*, 1971b). The formulae used are listed below. Modifications of the methods are discussed in the main text.

Leaf area:

$$A = b (nlw) \quad (4.5)$$

where A = leaf area (cm²), n = number of leaflets, lw = mean of length $\times$ mid-width (cm) for a sample of six of the largest leaflets, and b is a correction factor.

Leaf dry weight:

$$W = 0.102P + 0.21 \quad (4.6)$$

where W = leaf dry weight (kg) and P = petiole width $\times$ depth (cm²).

Trunk dry weight increase:

$$T = VS = (\pi r^2 h)S \quad (4.7)$$

where V is the volume increment of the trunk (litres/year), S is the density of dry trunk in (kg/litre), r = trunk radius (after removal of leaf bases), and h is annual height increment.

Trunk density:

$$S = 0.0076t + 0.083 \quad (4.8)$$

where t is the age of the palm in years from transplanting.

Bunch dry matter content:

$$D/F = 0.37X + 0.29 \quad (4.9)$$

where X is the fruit/bunch ratio, D is dry and F is fresh bunch weight in kg. If fruit/bunch ratio does not vary with treatments, it can be assumed to be 0.65, and the formula becomes $D = 0.53 F$.

production. Root growth is discussed further below (Section 4.2.1.4).

4.1.3.1 Leaf area

Hardon *et al.* (1969) estimated leaf area from measurement of a sample of the longest leaflets, using Equation 4.5. The correction factor, b , was found to range from 0.51 to 0.57 in different age groups, and also differed significantly between progenies (Mendham, 1971), but for most purposes a figure of 0.55 has been assumed. Henson (1993), in a study of palms ranging in age from the nursery up to 8 years after field planting, found that the best fitting relationship was $A = -0.25 + 0.455 nlm$. If the correction factor from Hardon *et al.* (1969) was used, leaf area might be overestimated by as much as 20%.

Tailliez and Ballo Koffi (1992) described an alternative method of estimating leaf area. This involved dividing the rachis into ten sections of equal length, counting the leaflets attached to each section, and measuring the length and width of one leaflet from each section. True leaf area is then obtained from the sum of the products nlm for each section, multiplied by an unspecified correction factor. This method is more laborious than that of Hardon *et al.* (1969), but probably more accurate, as variations in leaf shape should be accounted for to some extent. Corley and Breure (1981) found that the Hardon method was very sensitive to the position along the rachis from which the sample of leaflets was taken. Hirsch (1980) showed that leaf area was highly correlated with the fresh weight of leaflets, but the latter cannot be measured non-destructively.

Leaf area index, L , depends on area per leaf, palms per hectare and number of leaves per palm (Section 4.1.4.2). All of these can be measured, but Lamade (1997) showed that the leaf area index of an oil palm plantation could be estimated quite accurately from light interception, measured with an PCA-2000 Plant Canopy Analyser (Li-Cor Incorporated, Lincoln, Nebraska, USA). This method is much faster than measuring leaf area by the Hardon or Tailliez method, and counting leaves per palm, but the equipment is expensive. The instrument measures light penetration from several different angles simultaneously, and calculates L from the data. A key assumption is that leaflets are randomly arranged, but this is not true for oil palm canopies (Section 4.1.4.2), which may introduce some error. If the measurements of light interception are reasonably accurate, however, they could be used directly in Equation 4.4, rather than using measurements of L to estimate f (Section 4.1.4.2).

4.1.3.2 Leaf dry weight

Corley *et al.* (1971b) showed that leaf dry weight can be estimated from the width and depth of the petiole, measured at the junction of the rachis and petiole, i.e. the point of insertion of the lowest leaflet (Equation 4.6). For the total dry matter incorporated into leaves, the mean dry weight must be multiplied by the number of new leaves produced. The regular leaf arrangement (see Section 2.2.1.3) allows this to be recorded by marking the youngest fully open leaf with paint, and then counting the number of additional leaves a year later.

As Equation 4.6 gives a positive weight when P is zero, it is clear that it cannot apply to very young palms, with small values of P , although Corley *et al.* (1971b) did not specify this. Henson (1993) found that dry weight was overestimated for palms younger than 5 years. He found that the regression coefficient increased with palm age, from about 0.04 in 1-year-old palms, up to about 0.10 in 6-year-old palms. The latter figure is similar to that in Equation 4.6. In Sumatra, the regression equation $W = 0.078P + 0.395$ was obtained (BLRS, 2002). Leaflet, rachis and petiole dry weights were also said to be closely related to petiole cross section (leaflets = $0.0305P + 0.12$; rachis = $0.0327P + 0.071$; petiole = $0.01P + 0.41$).

4.1.3.3 Trunk dry weight increment

The annual growth increment of the trunk is represented by a cylinder, the volume of which is calculated from trunk radius (after removal of leaf bases) and annual height increment; to obtain dry weight increase (Equation 4.7), the volume must be multiplied by density, which was found to increase with age (Equation 4.8). Hirsch (1980) found trunk densities in Ivory Coast which were close to those predicted by Equation 4.8. In Sumatra, a similar regression was found ($S = 0.007t + 0.125$; BLRS, 2002). It should be noted that in some studies, usually where there were no obvious visual differences, trunk girth has been assumed to be constant for all treatments. This avoids the tedious work of removing leaf bases, but introduces further uncertainties in the results.

Equation 4.8 has the implication that the density of the new trunk increment increases with palm age, but this is misleading. Detailed measurements by Gray (1969) showed that the apical section of the trunk, in palms of all ages, had a low dry matter content. Apart from this apical section, density was fairly uniform, and increased with age. The trunk is a relatively small component of total dry matter production, and in most

circumstances the approximations involved may not be important, but users of the methods should be aware of possible distortions.

4.1.3.4 Bunch dry weight

This is a fairly constant fraction of bunch fresh weight, which is routinely recorded in most oil palm trials. A dry matter content of 53% is usually assumed, but if there are large differences of fruit/bunch ratio, bunch dry matter content is best calculated from Equation 4.9, as percentage dry matter varies with fruit/bunch.

4.1.3.5 Conclusions

A detailed description of the application of these methods is given by Breure and Verdooren (1995). A slightly simplified procedure, which does not require records of leaf production rate, was described by Breure and Powell (1988).

The formulae have been used extensively to estimate dry matter production, as discussed below. It appears that they can be used to rank treatments or progenies with reasonable confidence, but for accurate estimates of dry matter production, the constants in the equations should be checked under the particular circumstances of interest, as Henson (1993) and Mendham (1971) have shown that they cannot be assumed to be universally valid.

4.1.4 Components of dry matter production

In this section we discuss each of the parameters in Equation 4.4.

4.1.4.1 Incident radiation

Total solar radiation, S , is a function of climate, and is beyond management control. The climate of oil palm growing regions is reviewed in Chapter 3. Squire (1984a) discussed the instruments available at that time for radiation measurements. It is important to note that some instruments measure total short-wave radiation, over the wavelength range 300–2500 nm, whereas others measure only the photosynthetically active range (PAR, 400–700 nm). The latter is typically about half of total radiation, although the exact figure varies with season, time of day and atmospheric conditions. For growth analysis, S is usually expressed in terms of PAR, but this convention is not always followed, so care must be taken in comparing values of f and e .

4.1.4.2 Light interception

Light interception, f , can be estimated by measuring incident radiation above the crop, and the radiation reaching the ground below the canopy. Strictly, light reflected back from the canopy should be excluded, but this component is often ignored. Henson (1995a) found, in 10-year-old palms on a coastal soil in Malaysia, that 15% of total radiation was reflected, 70% was absorbed and 15% reached the ground. Absorption of PAR was much greater, at 90%, with only 3% reflected and 6% reaching the ground.

Measurement of light interception is laborious. Numerous light meter readings beneath the canopy must be taken, and must be compared with readings above the canopy, or in open space nearby. Squire (1984a) showed that light penetration below the canopy varied considerably with distance from the palm trunk, and described a suitable sampling scheme to give representative figures. The sampling scheme described by Lamade (1997) gives too much weight to points close to the palm.

Light is mainly intercepted by the leaves (although rachises and trunk also intercept some light). The proportion of total solar radiation intercepted is a function of leaf area index which, as noted above, is the product of mean area per leaf, number of leaves per palm and number of palms per hectare. Most work has been concentrated on the first and last of these factors; leaf area varies with palm age, and between progenies and agronomic treatments, while decisions on number of palms per hectare are an important aspect of management (see Chapter 9). Less attention has been paid to leaves per palm, which probably depends mainly on management (pruning during harvest of bunches), and in some studies it was assumed that the number of leaves per palm was constant across experimental treatments (e.g. Corley and Donough, 1992). This may be a reasonable assumption where the aim is to compare progenies, but Corley and Mok (1972) showed that nitrogen fertiliser increased the number of leaves per palm, and Corley (1973b) showed that the number was appreciably reduced at very high densities. Irrigation increased leaf number of young palms in Ivory Coast (Desmarest, 1967). Gerritsma and Soebagyo (1999) showed that the number of leaves per palm declined steadily with palm age, up to at least 11 years after planting (14 years in one trial). This decline continued beyond the point, at 9–10 years, where mean leaf area reaches a plateau (Hardon *et al.*, 1969; Corley and Gray, 1976a; Gerritsma and Soebagyo, 1999). Thus, L tends to reach a peak at the time that leaf area peaks, but then to decline slightly as leaf number decreases.

Light interception by many crops can be described by an equation of the form:

$$f = 1 - e^{-kL} \quad (4.10)$$

where k is a dimensionless constant, the 'extinction coefficient', with a value between 0 and 1, and L is leaf area index above the level of light measurement. The equation is for an exponential decay curve, and describes the observation that the light penetrating to a certain level in the canopy diminishes in proportion to the leaf area above that level. To estimate the extinction coefficient, f must be measured at a range of values of L . Light penetration can be measured to different depths in the canopy or, as has been done with oil palm, below the whole canopy where L varies with planting density or pruning regime. Squire found that for oil palm, Equation 4.11 fitted the data better than Equation 4.10, for $L > 2$ (Squire and Corley, 1987).

$$f = 1 - e^{-k(L-a)} \quad (4.11)$$

where a is a constant. This relationship, plotted as the logarithm of $(1 - f)$ against L , is illustrated in Fig. 4.1a.

Light interception depends not only on L , but also on canopy 'architecture'. If most leaves are arranged parallel to the sun's rays, they will intercept less radiation than if they are arranged perpendicularly to the sun. Low values of the extinction coefficient, k , are found for 'erectophile' canopies, in which leaves are predominantly vertically arranged, as in cereals (de Wit, 1965). Theoretically, such a canopy should be more efficient than a horizontal arrangement, because light is better distributed, with more reaching leaves at the base of the canopy. Thus, low light interception, for a given L value, is synonymous with good light distribution.

The extinction coefficient for PAR is higher than for total radiation, typically by a factor of 1.4 (Squire, 1984a), so it is essential to note the units used for light measurement before comparing k values from different data sets. A further complication in comparing oil palm with other crops is the non-linearity of the relationship between f and L at low L (Fig. 4.1a). This is probably attributable to the non-random spatial distribution of oil palm leaflets; Squire (1984a) showed large differences in light interception with distance from the palm trunk. For mature palms, $k = 0.34$ (total radiation) and 0.47 (PAR) are probably typical values (Squire and Corley, 1987; Henson, 1995a), although Breure (1988b) found a lower value in 14-year-old palms, 0.32 for PAR. All these values are low compared with many other crops, suggesting an erectophile leaflet arrangement,

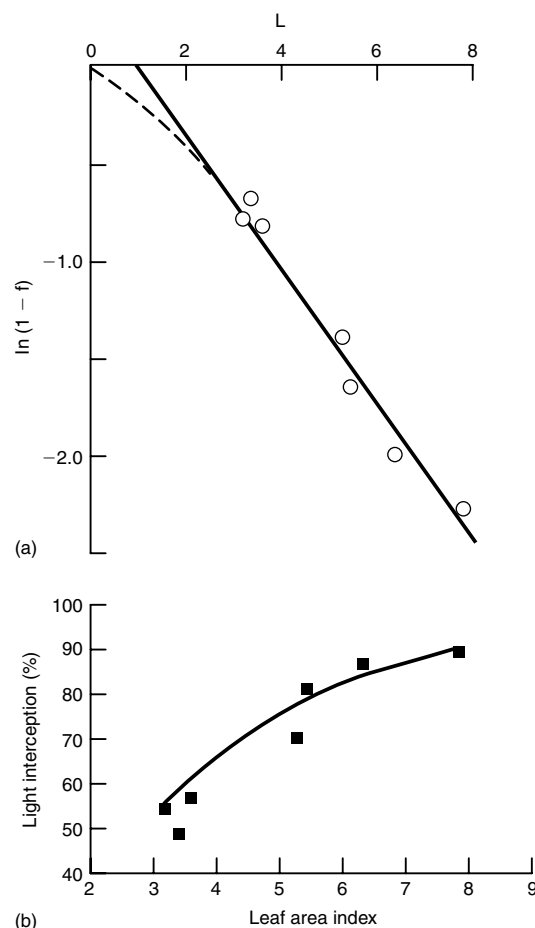


Fig. 4.1 Light interception and leaf area index. Figures for total radiation, not PAR, from Squire and Corley (1987). The equation is $f = 1 - e^{-0.34(L-0.3)}$ or $\log_e (1 - f) = -0.34(L - 0.3)$. For PAR, k would be 0.47, rather than 0.34. (a) Plotted on a logarithmic scale, showing a linear relationship, except at low leaf area index; (b) plotted on a linear scale, showing a plateau at high leaf area index.

but Corley (1976c) showed that the canopy of young field palms was 'plagiophile', intermediate between erect and horizontal. For densely packed nursery plants, where leaflet distribution is closer to random, k is larger (0.7 for PAR) and Equation 4.10 fits the data (Squire, 1984b). It should be noted that, if the standard methods overestimate true leaf area, as Henson's (1993) work suggested (Section 4.1.3.1), then L would also be overestimated, and thus k would be underestimated. This may partly explain the low values of k in comparison with other crops.

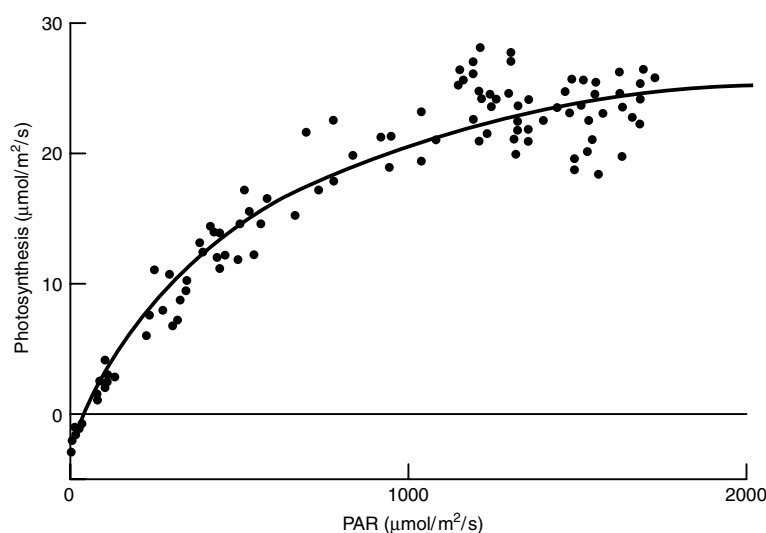


Fig. 4.2 Response of photosynthesis to increasing light intensity. (From Dufrene *et al.*, 1990.)

4.1.4.3 Photosynthesis and the conversion coefficient

The photosynthetic conversion coefficient, e , can be estimated from total dry matter production. Crop growth rate is measured, or estimated non-destructively, light interception is measured or estimated from L , S can be recorded, and e is then calculated from the relationship $e = \text{CGR}/fS$ (Squire, 1986). In this calculation, e is effectively a residual term, and includes not only any effects not accounted for elsewhere, but also the consequences of any errors in other measurements. For example, if leaf area, and hence f , is overestimated, e will be underestimated by a compensating amount. Thus, it can sometimes be difficult to interpret observed differences in e . Bonhomme (2000) noted that different values will be obtained depending on whether reflected radiation is allowed for or ignored, and on whether PAR or total radiation is measured. Although PAR is typically about 50% of total radiation, this cannot be used to convert from one set of units to the other, because of the different extinction coefficients for PAR and total radiation (see above).

The maximum values recorded for e in oil palm are about 1.3 g/MJ (Squire and Corley, 1987; Gerritsma and Wessel, 1997) or, adjusting for the oil content of bunches, $e^* = 1.6$ g/MJ (Section 4.1.4.4). These figures are little more than half those recorded for temperate arable crops, probably because of the large respiration loss from oil palm (see below).

For estimating e , dry matter production is normally measured over weeks or months, but rates of photosynthesis can also be measured or estimated more directly

over shorter periods. Short-term rates (seconds or minutes) are readily measured with a portable infrared gas analyser (IRGA), but short-term data from individual leaves are rarely correlated with total crop dry matter production (see, for example, discussion in Evans, 1993). There are simply too many variables involved in the scale-up from an instantaneous measurement on a single leaf to the average performance of a whole crop canopy over weeks or months. It is useful to find out what factors influence the photosynthetic rate of single leaflets, however, such information may be helpful in selection programmes (e.g. Smith, 1993a) and can be used in computer models. For example, photosynthetic light response curves can be combined with models of light penetration through the canopy to estimate canopy photosynthesis (e.g. van Kraalingen *et al.*, 1989).

Photosynthesis of the entire canopy can be measured over periods of hours or days by micrometeorological methods. A battery of sensors is used to measure fluxes of carbon dioxide, water vapour and heat above the canopy, from which rates of photosynthesis, respiration and transpiration can be calculated. Henson (1995a) and Maycock and Henson (1992) applied these methods to oil palms in Malaysia.

Light intensity: Photosynthetic rate of individual leaves of all crops with the C3 photosynthetic pathway shows a curvilinear relationship with light intensity. Figure 4.2 shows a typical light response curve. At low light levels, light is the limiting factor and photosynthetic rate is directly related to light intensity. The 'light compensation point' is the light intensity where photosynthesis and respiration are equal; below this

light intensity, there is a net outflow of carbon dioxide from the leaf.

At high light levels, photosynthesis becomes 'light saturated' and the rate of carbon dioxide uptake through the stomata becomes the main limitation. The light saturated rate of photosynthesis is known as $A_{\max}$. Gerritsma (1988) studied six different progenies and found that light saturation occurred between 100 and 200 W/m² absorbed PAR. Hong (1979) observed light saturation at about 400 $\mu\text{moles/m}^2$ per second, while Dufrene and Saugier (1993) and Henson (1995b) observed it at about 800 $\mu\text{moles/m}^2$ per second. These two figures (both for PAR) are approximately equivalent to the two extremes in Gerritsma's study. Henson (1991c) compared leaves of young palms grown in shade and in full sunlight, and found that the former had a lower light compensation point and a lower rate of dark respiration, adaptations that would result in greater net rates of photosynthesis under shade. However, shaded palms had lower $A_{\max}$ than leaves developed in full sun.

Total canopy photosynthesis does not generally show light saturation, in contrast to individual leaves. This is probably because, as upper leaves become saturated by increasing light intensity, penetration of light to leaves lower in the canopy also increases, so that those leaves photosynthesise more rapidly. Henson (1995a, b) showed that total canopy photosynthesis, measured by micrometeorology, was more or less linearly related to solar radiation up to 700 W/m², provided that vapour pressure deficit was not limiting (see Section 4.3.3.2). One might expect, therefore, that the smoke haze that was widespread in South-east Asia in the 1980s and 1990s would reduce canopy photosynthesis. However, Henson (2000), using a model of oil palm canopy photosynthesis, found that the reduced radiation led to smaller atmospheric vapour pressure deficit and lower temperature. These changes were favourable to photosynthesis, and tended to offset the direct effect of lower radiation on photosynthesis, so that photosynthesis (and yield) might actually be higher under haze. In Ecuador, despite less than 900 sunshine hours per year, Mite *et al.* (2000) recorded annual yields of over 28 t FFB/ha under irrigation, confirming that low radiation does not necessarily limit yield.

These observations illustrate the problems of trying to express the complex process of dry matter production by a simple equation such as Equation 4.4. All else being equal, dry matter production does depend on S , but high values of S will also affect stomatal aperture and leaf temperature, and the limiting effect of these on photosynthesis and e may sometimes be greater than any direct benefit of high total radiation (see also Fig. 4.10, Section 4.3.3.2).

Respiration: Crop growth rate is the net result of photosynthetic production (gross photosynthesis) minus respiration. A large proportion of the carbohydrate produced in photosynthesis is used in respiration, being broken down to carbon dioxide and water, and releasing energy in the form of adenosine triphosphate (ATP). In plant growth analysis, respiration is usually treated simply as a loss, but the energy is used both in synthesis of the components of new plant tissues, and for 'maintenance' of existing tissues. The latter consists mainly of the metabolic costs of protein and cell membrane turnover. There are several difficulties with the standard treatment of respiration in growth analysis studies, however. Expressing respiration as a loss of photosynthetic product has the implication that reducing respiration would increase growth, which is clearly wrong. The apportioning of respiration between growth and maintenance is supposed to overcome this. Amthor (2000) gave a comprehensive review of the subject. Hansen *et al.* (1998) provided a contrary view, pointing out that the division into growth and maintenance respiration is mainly a convenience for crop modelling, but there are neither distinct growth and maintenance pathways, nor separate pools of substrate. They considered that the concept has not led to much useful insight, or to the development of crop varieties with improved growth rates.

Crop respiration cannot easily be measured directly, but it has been estimated in various ways. Penning de Vries (1972) estimated respiratory requirements for plant growth from knowledge of the biosynthetic pathways for different classes of compounds. These estimates have been widely used in growth modelling of many crops, including oil palm (Breure, 1988a; Dufrene, 1989; van Kraalingen *et al.*, 1989), but this method of estimating growth respiration assumes perfect metabolic efficiency, a condition that may rarely be met. Penning de Vries (1975) also proposed a method for estimating maintenance respiration requirements for different tissues, but this does not have quite such a sound biochemical basis as the estimates for growth respiration, and maintenance requirement is undoubtedly dependent on conditions.

Dufrene (1989) found very high respiration rates in inflorescences at anthesis, and this has been confirmed in Malaysia (Henson and Chang, 2000). In some plant species, high respiration rate leads to high flower tissue temperatures, serving to attract pollinating insects, and this may be the case with oil palm. Apparently wasteful processes, such as this heat generation, are not accounted for in the basic growth/maintenance model of respiration (see Amthor, 2000).

Despite doubts as to the exact levels of respiration, there is agreement among various authors that between 60 and 80% of gross assimilation is respired (Corley, 1976c; Breure, 1988a; Dufrene, 1989; Henson, 1992; Lamade and Setiyo, 1996a), with the greater part of this being maintenance respiration. Thus, e is strongly influenced by rates of respiration, as well as photosynthesis.

4.1.4.4 Partitioning of dry matter

The term 'harvest index' was coined by Donald (1962), to describe H , the proportion of total dry matter in the harvested product. For oil palm, the harvested products are oil and kernels. Corley *et al.* (1971a) used the term 'bunch index' (BI), for the proportion of dry matter incorporated in fruit bunches. The product of bunch index and oil to (dry) bunch ratio is the harvest index; oil to fresh bunch weight is routinely measured in oil palm trials, and Corley *et al.* thought it useful to look separately at the other 'component' of harvest index. Squire (1984b) drew attention to the high energy requirement for oil synthesis, and suggested that bunch index might be calculated in energy terms, rather than dry matter. The energy content of oil is about 2.1 times the energy content of 'non-oil' bunch dry matter, so the adjustment is made by multiplying the oil content of the bunch by 2.1. The abbreviations BI* and e^* are sometimes used, the asterisk indicating that the adjustment for energy content has been made, to give a 'non-oil equivalent' of actual dry matter. Squire later noted that, for comparison of agronomic treatments, this correction was not too important, because differences in oil/bunch between treatments were usually small (Squire, 1986). Genetic differences in oil/bunch may be large, as discussed in Chapter 5.

4.2 VEGETATIVE GROWTH AND PARTITIONING OF DRY MATTER

The assimilates produced in photosynthesis are distributed among the trunk, leaves, roots and inflorescences (predominantly bunches, as male flowers weigh little). For above-ground dry matter, the 'overflow model' (Section 4.1.2.1) states that vegetative dry matter production per palm at a given palm age is more or less constant, with yield depending on the excess assimilates available, once vegetative requirements are satisfied. Figure 4.3 illustrates this point: as total dry matter production per palm increases, bunch yield increases almost in direct proportion, while vegetative dry matter production shows only a slight upward trend. In some

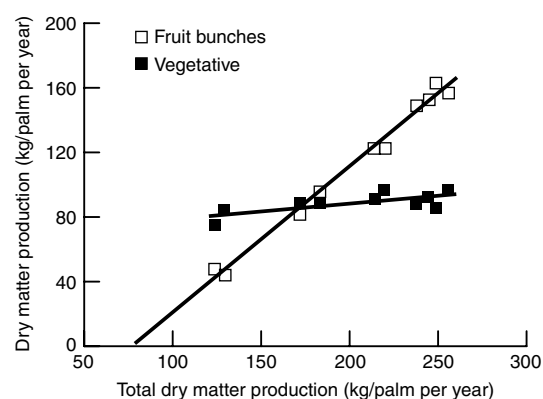


Fig. 4.3 Dry matter incorporated into vegetative tissues and bunches, compared with total dry matter production per palm. The lines are fitted regressions (both with slopes significantly different from zero), and indicate that 91% of all additional dry matter, above a threshold of 77 kg/palm per year, goes into bunches. Bunch dry matter is adjusted for the energy content of the oil. Data from Corley (1973b) for 6–7-year-old palms in a density trial, plotted as in Squire (1990).

computer models of oil palm growth, such as that of van Kraalingen *et al.* (1989), this overflow model has been used to describe partitioning, and it can give reasonable results when dry matter production over periods of a year or more is considered. However, as discussed in more detail in Section 4.3, in some circumstances it is clearly an oversimplification. In particular, vegetative growth appears to respond to differences in soil fertility or fertiliser application (Section 4.3.2).

4.2.1 Vegetative growth

Corley *et al.* (1971a) drew attention to the relative constancy of VDM per palm, and Corley (1973b) found no significant effects of planting density on VDM, over a range from 112 to 368 palms/ha. Subsequent work has shown that VDM is not constant, but it is much less variable than bunch yield. Corley and Donough (1992) found significant reductions in VDM with increasing density in five out of seven clones; Corley (1976a) showed that severe pruning reduced VDM by 4% (but reduced yield by 65%). Conversely, when yield was reduced by removal of 75% of inflorescences, VDM increased (Corley and Breure, 1992), but a 45% reduction in yield was associated with only a 5% increase in VDM. Removal of all inflorescences resulted in a 22% increase in VDM.

4.2.1.1 Leaf production rate

Development of the leaf is described in Chapter 2. The number of new leaves produced by a palm is low in the first year after field planting, but may be as high as 40/year 2 years after planting; it then declines steadily with age (Jacquemard, 1979; Gerritsma and Soebagyo, 1999), stabilising after 8–12 years at about 20–24 leaves/year.

The relative constancy of the leaf production rate for mature palms, in widely differing conditions, underlies the constancy of VDM. Annual leaf production is quite similar in West Africa, with a regular dry season, and in parts of the Far East with little or no dry season. Broekmans (1957b) recorded an average production by 10–15-year-old palms in Nigeria of 22.5 leaves/year. In Malaysia, the average over the same age range was 20.7 (Corley and Gray, 1976a). In Indonesia, Gerritsma and Soebagyo (1999) recorded figures of 22.5–23 leaves/year, and Breure (1994) found between 21 and 24.5 leaves/year in Papua New Guinea. In Congo, Beirnaert (1935b) recorded 18–26 leaves/year.

Careful study shows that the leaf production rate does vary, however. As discussed in later sections, small but significant effects of fertilisers, irrigation and planting density on leaf production rate have been observed.

4.2.1.2 Leaf area and weight

Leaf area and dry weight may show significant responses to fertilisers, but are not very sensitive to other factors.

4.2.1.3 Trunk growth

Annual height increment depends on the rate of leaf production and the height increment per leaf, or internode length. Jacquemard (1979) showed that height growth was negligible in the first 3 years after planting. Growth rate then increased, and was more or less constant from about 6 years until at least 25 years. Internode length does not appear to have been studied explicitly, but could be derived from height increment and leaf production data. For example, if leaf production decreases with increased planting density, and height increases with density (Section 4.3.1.3), this must indicate an increased internode length.

4.2.1.4 Root growth and turnover

The dynamics of partitioning to roots have not been studied, but it seems likely that roots tend to take priority over bunches for dry matter, as do leaves. However,

root growth may not show the same constancy as above-ground vegetative growth: the large variation in measured root biomass between different soils and environments (Section 4.1.2.3) suggests that there are likely to be differences in annual dry matter incorporated in the root system.

In the early oil palm growth analysis work, the net annual increase in total weight of roots was taken as the only possible estimate of root dry matter production. It was recognised that there would be additional dry matter used for the replacement of old roots by new, but this root turnover is very difficult to measure. With one exception, the dry matter production figures in Table 4.1 are for net annual increase in weight. The exception is Dufrene's (1989) study: he stated that, from the work of Ruer (1968), 'it can be deduced' that 15% of primary roots, 31% of secondaries and 57% of fine roots are replaced each year (the root system is described in Chapter 2). By applying these figures to observed root biomass, Dufrene estimated dry matter incorporated in roots to be 11.5 t/ha per year.

Lamade *et al.* (1996b), in Benin, estimated root turnover from measurements of soil carbon balance. They measured carbon dioxide production of soil samples with, and again after removal of, roots. The respiration of soil without roots was assumed to result from microbial breakdown of palm residues (pruned leaves and dead roots). Given an estimate of the weight of pruned leaves, the amount of dry matter in dead roots (root turnover) was calculated at about 9 t/ha per year, quite close to Dufrene's figure. From the description of the method, it appears that this would also include root exudates subsequently utilised by soil flora, and external mycorrhizal hyphae, as well as root turnover.

Henson and Chai (1997) estimated root turnover in Malaysia from soil carbon balance, using a slightly different method from Lamade *et al.* Soil respiration was measured, and an estimate of root respiration, calculated from measured root biomass, subtracted. Respiration from microbial breakdown of above-ground dry matter was estimated from the weight of pruned leaves. Root turnover was calculated to be 2.9 t/ha per year, with a further biomass increase of 1.6 t/ha per year. The total dry matter incorporated in roots was thus about 4.5 t/ha per year.

Henson and Chai (1997) also used a second method, involving the extraction of soil cores, refilling the holes with root-free soil, and measuring regrowth of roots into the cores 6 months later. This gave estimates of total root growth, at six sites including two age groups, ranging from 1.2 to 4.4 t/ha per year. Root turnover, calculated from the difference between total root

growth and net increase in biomass, ranged from zero (in one group of 3–4-year-old palms) to 4 t/ha, with an average for four groups of 9–10-year-old palms of 2.1 t/ha per year.

There are problems with all the methods used, but as with the root biomass figures, the estimates of root turnover from the Far East are much lower than those from Africa. Thus, it appears that root growth is less constant across environments than above-ground vegetative growth. One reason for high turnover in Africa may be that large parts of the root system die back during the annual dry season (Forde, 1972).

4.2.2 Partitioning between vegetative growth and bunch production

The 'overflow model' was based on observations that bunch production is more variable between environments than is vegetative dry matter production (Section 4.1.2.1; see also Section 4.2.1 and Fig. 4.3). Squire and Corley (1987) found a linear relationship between intercepted radiation per palm and yield of bunches, when interception was modified by leaf pruning or by high density planting (Fig. 4.4). Squire (1986) also found a linear relationship between e and bunch yield in his analysis of fertiliser trials. These and similar observations have been taken as indicating that bunch yield is source limited; that is, limited by the supply of carbohydrates from photosynthesis. As discussed below, however, this may be an oversimplification.

4.2.2.1 Young palms

Henson (1990b, 1991d) produced several pieces of evidence to suggest that rate of photosynthesis is stimulated by the presence of developing bunches, acting as sinks for assimilates, at least in young palms. First, the rate of photosynthesis in young palms nearly doubled 2 months before the first bunches were harvested, at about the time that assimilates would have been required for oil synthesis (Fig. 4.5). Secondly, the rate of photosynthesis of young palms was correlated with the number of bunches developing on the palm (Fig. 4.6). Thirdly, when 75% of the leaves were removed from young palms, the rate of photosynthesis of the remaining leaves increased in palms carrying bunches, but not in those without bunches. At the same time, the level of trunk carbohydrates fell in fruiting palms, but not in non-fruiting palms. Gerritsma (1988) also found an increase in the rate of photosynthesis after pruning, but the difference was smaller than in Henson's work, and he only found a small, non-significant, effect of fruit

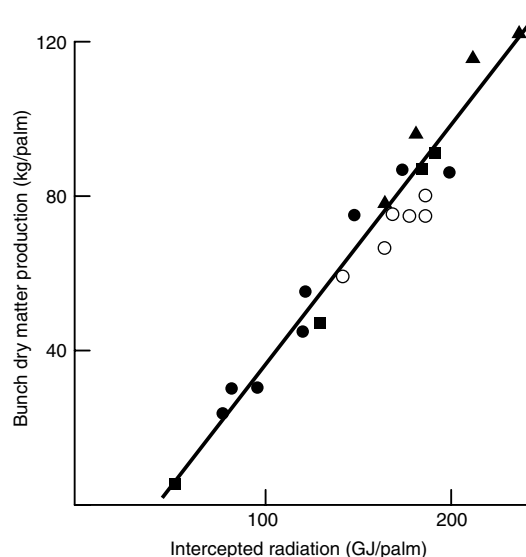


Fig. 4.4 Yield of bunches (dry weight) in relation to light interception. Yield increases in direct proportion to intercepted radiation. (From Squire and Corley, 1987.)

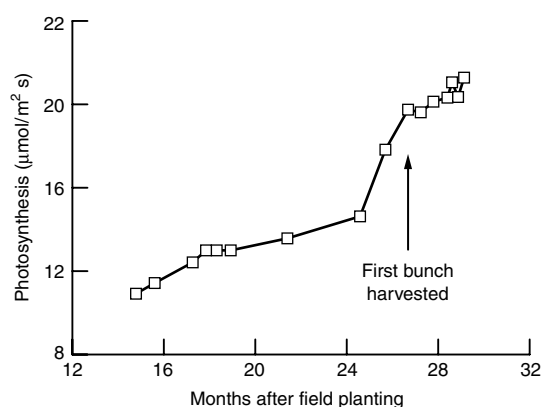


Fig. 4.5 Photosynthesis of individual leaves of young palms. A large increase in rate occurred shortly before the first bunch was harvested. (From Henson, 1990b.)

removal on $A_{\max}$. Quite severe defoliation of young palms, before fruiting starts, has a negligible effect on subsequent yield (Wood *et al.*, 1973; Liau and Ahmad Alwi, 1995), suggesting that growth at this stage is not limited by supply of assimilates from photosynthesis.

These results suggest feedback control of photosynthetic rate by sink demand, perhaps mediated through

accumulation of carbohydrates in the leaflets. Henson (1990b) found higher leaf carbohydrate levels in non-fruiting than in fruiting palms; similar effects have been observed in many crops (reviewed by Evans, 1993). It seems reasonable to conclude that potential photosynthesis of oil palms before fruiting starts is more than sufficient for vegetative growth requirements; growth at that stage is sink limited.

4.2.2.2 Fruiting palms

Once fruiting starts, photosynthetic rate increases in response to the extra sink demand (see Figs 4.5 and 4.6), and the overflow model implies that yield becomes source limited, while vegetative growth remains sink limited. However, more detailed analysis shows that, while vegetative growth clearly has a higher priority

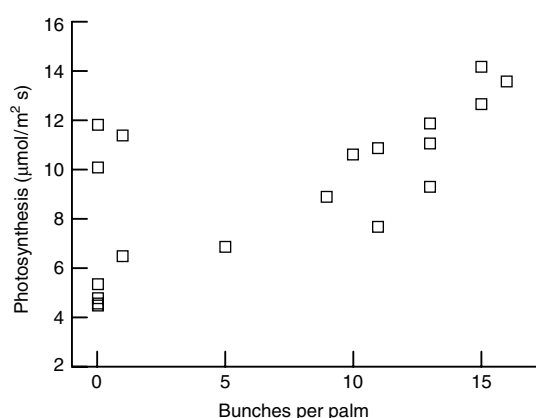


Fig. 4.6 Photosynthesis of individual leaves in relation to number of bunches per palm. (From data of Henson, 1990b.)

than yield, there is a balance between the competing sinks, with vegetative growth constrained to less than the maximum possible, and thus also source limited. This is illustrated in Table 4.3. Removal of 50% of inflorescences had only a small effect on e and CGR: the size of the remaining bunches increased, and leaf size increased slightly, indicating that, without bunch removal, both bunch yield and vegetative growth were limited by assimilate supply (source activity). Removal of 75% or 100% of inflorescences led to further increases in vegetative growth, but with few or no bunches, sink demand had become limiting, and there were large reductions in e and CGR. It is most unlikely that the difference was made up by additional (unmeasured) trunk storage, as the total biomass of trunk in a 4.5-year-old palm is less than the 60 kg reduction in measured dry matter production (see Table 4.2).

Bealing and Haniff Harun (1989) suggested that yield may always be sink limited, through effects of water stress on bunch number (Sections 4.4.4 and 4.4.5), and that the apparent constancy of VDM indicated that source activity was more than adequate to support vegetative growth in all circumstances. Part of their argument was that VDM does not increase in response to reductions in bunch yield, but this is not so: as noted above, in mature palms, if the bunch sink is reduced or missing, extra dry matter may be allocated to 'luxury' vegetative growth (see Table 4.3). The same phenomenon occurs in sterile *pisifera* palms, which tend to be much more vigorous than their *dura* and *tenera* sibs. Despite these observations, there is some merit in the point made by Bealing and Haniff Harun (1989). If one looks simply at dry matter allocation over long periods, yield appears to be source limited, but if short-term variation is considered, it becomes clear that the situation is more complex.

Table 4.3 Effects of continuous inflorescence removal on above-ground dry matter production

Inflorescences removed	Vegetative growth			Mean bunch weight (kg)	Dry matter production (kg/palm)				f (%)	e (g/MJ)
	Leaf weight (kg) ^a	New leaves/year	Trunk height (cm)		Bunches	Leaves	Trunk	Total		
None	1.68	31.8	101	4.0	81.6	53.4	10.0	145.0	60	1.04
50%	1.72	32.6	110	5.4	64.6	56.1	11.6	132.3	60	0.95
75%	1.72	33.2	111	6.7	44.4	57.1	12.5	114.0	61	0.81
100%	1.83	34.9	122	—	0.0	63.9	16.4	80.3	63	0.54
Standard error	0.045	0.3	2.7	0.1	1.5	—	—	—	—	—

Recalculated from data of Corley and Breure (1992); f estimated from L ; palms 4.5 years old, in Johor, Malaysia.

^aLeaf weights given by Corley and Breure were calculated incorrectly from petiole cross-section figures; data here are correct.

4.2.2.3 Short-term fluctuation in bunch dry matter requirements

The main demand for carbohydrate for bunches comes over the last few weeks of bunch development (Fig. 4.7). Henson (1997) used Fig. 4.7 to estimate monthly assimilate requirements for the actual yield harvested from two oil palm stands. As might be expected, the month-to-month fluctuation in harvested yield was greater than that for assimilate requirement, because the assimilate requirement is spread over several months of bunch development, but there was still typically a two-fold difference between peak and trough months for assimilate requirement.

Henson and Chai (1998) used the canopy model of van Kraalingen *et al.* (1989) to estimate monthly dry matter production. They showed that the predicted availability of assimilates and the requirements for yield, as calculated by Henson (1997), followed quite similar seasonal patterns, but also that the assimilate requirement for actual yield sometimes exceeded the predicted assimilate supply. They also noted that seasonal fluctuation in yield is due mainly to fluctuation in bunch number (see also Brédas and Scuvie, 1960), which is determined many months before anthesis, long before the demand for assimilates becomes significant. It is possible that source activity, directly or indirectly, affects bunch number, so that over long periods yield matches assimilate supply,

but it is clear from the above points that, in a strict sense, yield cannot be entirely source limited.

4.2.2.4 Trunk storage

As noted above, Henson and Chai (1998) found that the assimilate requirement for bunch yield sometimes exceeded the assimilate supply. Corley (1976c) observed that bunch production continued for some months after severe and continuous defoliation, with nearly 60 kg of bunches (dry weight) being produced per 10-year-old palm. These and other observations suggest the existence of stored reserves that can be mobilised when current photosynthesis falls short of demand. The trunk is the obvious storage organ, because it constitutes about 50% of the above-ground standing biomass by the time a plantation is 10 years old (see Table 4.2), and contains a large volume of living, parenchymatous tissue.

Henson *et al.* (1999) measured the carbohydrate contents of palm trunks. Most of the carbohydrate (from 54 to 82%) was in the form of soluble sugars, predominantly sucrose. There was an average of 37 kg extractable carbohydrates in the trunks of 8-year-old palms, sufficient to produce about 20 kg of bunch dry matter, or 38 kg of fresh fruit bunches (FFB). Gray (1969) found 48 kg per palm of extractable carbohydrate in the trunks of 8.5-year-old palms, and over 70 kg in palms more than 10 years old.

In Henson and Chai's modelling study (1998), trunk reserves were assumed to be equivalent to 18% of total trunk biomass, based on Henson *et al.* (1999). The discrepancies between the assimilate requirement for bunch yield and the predicted supply could be met quite easily by trunk reserves of this order. Henson (1999b) found no correlation between actual trunk carbohydrate levels and those predicted by the model, but he considered alternative ways in which the assimilates required in peak months might be provided, and concluded that it was unlikely that either an increase in photosynthetic rate or a reduction in respiration losses could make up the shortfall.

4.2.3 Conclusions

The overflow model implies source limitation of yield, and over long periods it appears that bunch numbers and weights are restricted by assimilate supplies. However, as discussed in Section 4.4, these yield components are determined many months before harvest, yet the main demand for dry matter is only in the last few weeks of bunch development. Thus, if there is a limiting effect of assimilate supply on yield, it can only

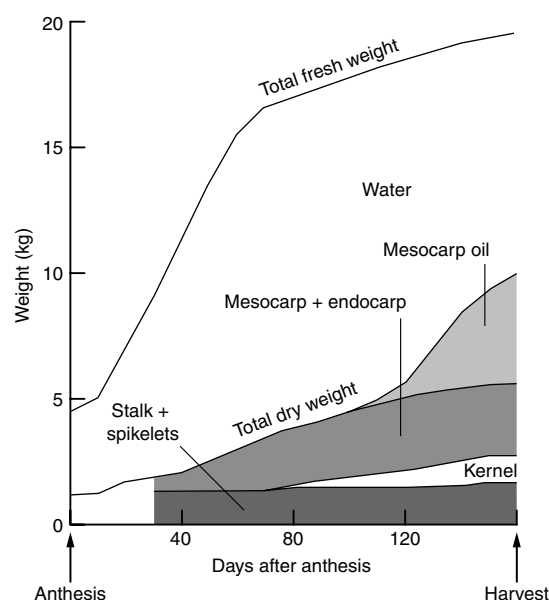


Fig. 4.7 Weight of bunch components over the course of development from anthesis to harvest. (From Corley, 1986.)

act to maintain a long-term balance, with trunk storage probably providing the buffering capacity necessary to meet short-term imbalances.

4.3 ENVIRONMENTAL AND MANAGEMENT FACTORS

In this section, the effects of environment on oil palm dry matter production, and its components as defined in Section 4.1.4, are discussed.

4.3.1 Effects of planting density

The relationship between total dry matter production (CGR) and planting density is shown in Fig. 4.8. In terms of Equation 4.4, the main effect of increasing planting density is to increase light interception. In Papua New Guinea (PNG), CGR was higher than at the same density in Malaysia (Fig. 4.8a), but this is mainly because growth was more vigorous in PNG. When the data are plotted against L , in Fig. 4.8b, the curves lie closer together. Crop growth rate reaches a maximum of over 35 t/ha per year, at a leaf area index of 8–9. To obtain such values of L , planting densities of 200 palms/ha or more are needed.

The response of fruit bunch yield (dry weight, approximately 50% of FFB yield; see Section 4.1.3.4), to density is different, with maximum yield at an intermediate density. When plotted against L , the trends in the two environments are similar, with an optimal leaf area index between 5 and 6. At higher L values light interception is nearly complete, so total dry matter production per hectare reaches a plateau, independent of palm number. Further increases in the number of palms per hectare will mean less dry matter produced per palm. Because of the relative constancy of dry matter requirement for vegetative growth per palm (Section 4.1.2.1), VDM per hectare will increase linearly with density, so a diminishing amount will be left over for bunch production (see Section 9.3.1 for further discussion). We may note that this explains the response of yield to planting density in terms of competition between palms for light, but in many crops below-ground competition for water or nutrients may be just as important (Tinker and Nye, 2000). No work on below-ground competition has been done with oil palm (but see Section 4.3.3).

4.3.1.1 Light interception and planting density

As noted elsewhere, L is the product of leaf area, leaves per palm and the number of palms per hectare or

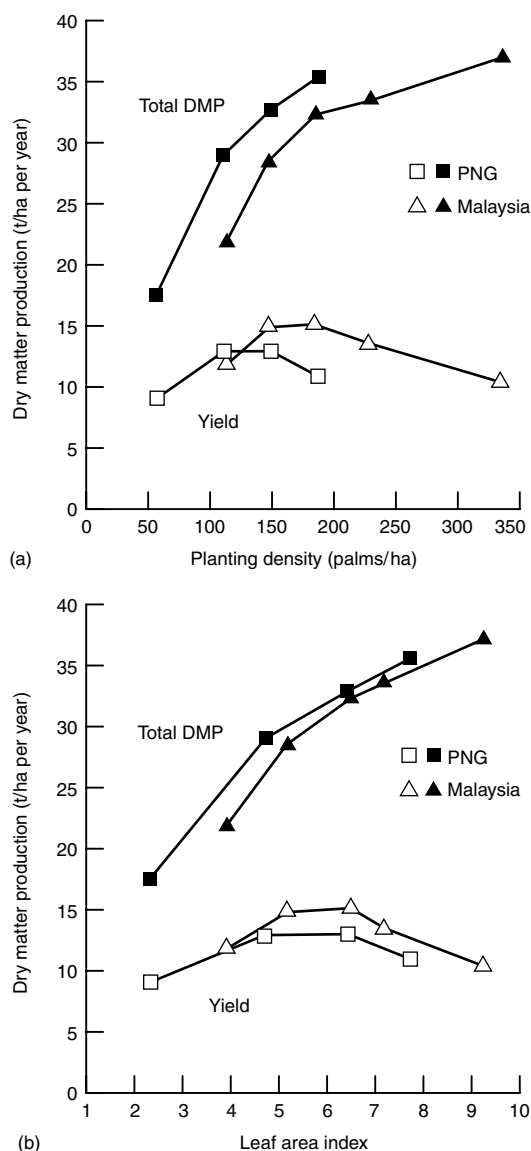


Fig. 4.8 Dry matter production (CGR) and yield at different planting densities. (a) Plotted against planting density; (b) plotted against leaf area index. (Data for Malaysia from Corley, 1973b; for Papua New Guinea from Breure, 1977.)

planting density. Density also has an indirect effect on L through number of leaves per palm, which is reduced at high densities (Corley, 1973b; Rao *et al.*, 1992). Mean leaf area is little affected by density, however (Corley and Donough, 1992; Rao *et al.*, 1992). Rao *et al.* found no change in number of leaflets per leaf, or

in leaflet length, but a slight increase in leaflet width, indicating a slight increase in leaf area with density.

At very high planting densities, the number of leaves per palm is reduced. Corley (1973b) found this to be the case even if no pruning was done, and suggested that leaf life was reduced under the low light intensity at the base of a very dense canopy, but a reduction in the rate of leaf initiation may also be involved (Section 4.4.3.1).

In mature palms at standard planting densities, leaf area indices of 5–6 are commonly observed. Figure 4.1b shows that, at $L = 6$, light interception is about 85%. Thus, even large increases in planting density cannot increase f of a mature stand by more than about 15%.

Complications arise because the optimal density changes with age. Oil palms start to yield some years before they are fully grown; bunch production may start 2.5 years after field planting, while, as already noted, the palm crown does not reach its final size for up to 10 years, so during the first few years of production the optimal density is constantly changing. Choice of planting density is thus a compromise between maximising early yields, which demands a high density for high light interception, and avoiding excessive inter-palm competition at maturity, needing a lower density. This subject is discussed further in Chapter 9. At this juncture, the important point is that any effect of higher than standard planting density on light interception is quite small, except in the early years.

4.3.1.2 Photosynthetic conversion and planting density

Several studies have shown e to increase with increasing planting density (Squire and Corley, 1987; Subronto *et al.*, 1991; Corley and Donough, 1992), but the reasons for this are not clear. Squire and Corley (1987) suggested that it might be due to decreasing respiratory losses as the balance between vegetative growth and bunch production changed, or to a reduction in root growth (not measured in most studies) at higher density. If f is estimated from leaf area index and Equation 4.11, rather than measured directly, then changes with density in the relationship between f and L could lead to errors in the estimation of e , but Corley and Donough (1992) measured f directly, and still found an increase in e with density.

It has been suggested that planting density has an effect on maintenance respiration: Breure (1988a) found that the difference between modelled gross photosynthesis and requirements for growth, which he assumed to represent maintenance requirement,

diminished, on a per palm basis, as density increased. In the model of van Kraalingen *et al.* (1989) constant rates of maintenance respiration per unit biomass of different organs were assumed, with surplus assimilate going to bunches. The model underestimated bunch yield at high densities, but not at low ones. Thus, in both cases there appears to be insufficient assimilate at high density to meet all of the requirements for growth, yield and maintenance respiration. Breure (1988a) suggested that maintenance respiration of leaflet tissues might be lower when photosynthetic rate per unit area was reduced at high density, and quoted McCree's work on clover in support (McCree, 1982). Henson (1991c) subsequently confirmed that dark respiration rate of older, shaded leaves was lower than that of young, unshaded leaves. If there is an increase in e with density, therefore, this appears the most likely explanation at present.

4.3.1.3 Partitioning and planting density

The clearest manifestation of the overflow model is in the response to planting density. The lower the density, the less the competition between palms for light, and the greater the dry matter production per palm. As dry matter production increases, Fig. 4.3 shows that about 90% of additional dry matter goes into bunches, and 10% to additional vegetative growth. At very low densities, where competition between palms is absent, a single palm may produce the equivalent of nearly 400 kg dry matter per year (excluding roots), with 65% of this being incorporated in bunches, to give an FFB yield of over 300 kg/palm (Breure, 1988a, b, and unpublished; Breure *et al.*, 1990; see Table 9.1: data for palms planted at 56/ha).

We have noted in Section 4.2.1 that there is a slight effect of density on vegetative growth, and it appears that this is mainly due to changes in the rate of leaf production. Corley and Donough (1992) found that leaf production declined with increasing density in all seven clones studied, although in one clone the trend was not statistically significant. Leaf area and dry weight, in contrast, are not much affected by planting density. Corley (1973b) found no significant responses, and Corley and Donough (1992) found a significant reduction in petiole cross-sectional area with increasing density in only one of seven clones. Another clone showed a significant increase in leaf area with density.

Visual appearance suggests strong effects of planting density on height, but Corley and Donough (1992) found that height, measured to the base of leaf 41, only

increased significantly with density in two out of seven clones, and in one clone it was significantly reduced. The etiolation effect so clearly visible in high-density plantings appeared to be more due to an increase in rachis length, which was highly significant for all clones. Other studies have given similar results: Tayeb Dolmat *et al.* (1995) observed an 8% increase in trunk height between 120 and 200 palms/ha, and a 14% increase in rachis length. Breure (1977) recorded a 9% increase in height and a 13% increase in rachis length between 56 and 186 palms/ha.

4.3.2 Effects of fertilisers

Corley and Mok (1972) showed that nitrogen and potassium fertilisers increased dry matter production and yield in Malaysia, and Lo *et al.* (1973) suggested that measurements of VDM might be used in diagnosis of fertiliser requirements. Breure (1977) observed an increase in crop growth rate in response to a combined nitrogen, potassium and magnesium application.

4.3.2.1 Light interception and fertilisers

One of the effects of fertilisers is to increase leaf area (Corley and Mok, 1972; Breure, 1977), but Corley (1985) showed that, although application of nitrogen and potassium to mature palms resulted in a 30% increase in leaf area, this led to only a 7% increase in f . Squire (1986), in an analysis of results of 22 Malaysian fertiliser trials, similarly found that fertilisers had only small effects on f . This is because in a mature plantation f is already high, so increasing leaf area and L does not make much difference. The response in f is likely to be greater in young palms, where light interception is still quite low, but responses of young palms to fertilisers do not appear to have been analysed in this way.

4.3.2.2 Photosynthetic conversion and fertilisers

Corley (1985) reanalysed data from Corley and Mok (1972), and showed that application of nitrogen and potassium fertilisers increased e by 29% (compared with only a 7% increase in f ; see above). Squire (1986) showed that the main effect of fertilisers was to increase e , and he found that e was positively correlated with leaf potassium content (Squire, 1990). Subronto *et al.* (1991) also showed that e increased in response to fertilisers. It seems probable that these effects of nutrients result from changes in photosynthetic rate of individual

leaflets, but there is little information on this. Corley (1976c) quoted data from pot trials with seedlings, showing that nitrogen deficiency reduced leaf chlorophyll content, stomatal conductance and $A_{\max}$, while potassium deficiency reduced stomatal conductance. Gerritsma (1988) found that palms with magnesium deficiency had lower photosynthetic rates.

4.3.2.3 Partitioning and fertilisers

Corley and Mok (1972) found that nitrogen fertiliser application increased the rate of leaf production; Gurmit (1990) also observed increases in some trials, but potassium caused a slight reduction in rate of leaf production in one trial; leaf magnesium content was quite high, so this was probably not due to magnesium deficiency, which is sometimes induced by heavy applications of potassium.

Responses of leaf dry weight and leaf area to fertilisers are regularly observed. Ruer and Varechon (1964) showed that petiole cross-section was increased by potassium fertiliser, and Corley and Mok (1972) found an increase in leaf area. These effects have been confirmed by Foster and Prabowo (1996b), Kee and Chew (1993) and Gurmit (1990). Nitrogen has been shown to increase leaf area, leaf dry weight and rachis length in several trials (Gurmit, 1990; Kee and Chew, 1993), and phosphate had similar effects in one trial (Gurmit, 1990). Wilkie and Foster (1990) observed an increase in leaf area index after applying nitrogen in PNG. Fertilisers may increase trunk growth rate; Breure (1977) recorded a 5% increase in trunk height from application of an N–K–Mg mixture in PNG.

The overall effect of fertilisers on partitioning is not straightforward. If leaf area and weight are increased, but f is already high, there will be little or no increase in f , and perhaps therefore no increase in dry matter production. Increased vegetative growth could mean that the assimilates available for bunch production are actually reduced. Breure (1977) observed this response at high density in PNG. If, however, fertilisers increase e , as well as leaf size, then dry matter production per palm should be increased, and bunch index and yield will be maintained or increased. At lower densities, this was the response in Breure's trial.

4.3.3 Water

As discussed in Chapter 3, seasonal water deficit is probably the most important climatic factor affecting oil palm yield. When evapotranspiration exceeds rainfall (or rainfall plus irrigation), soil water content decreases,

and may reach a point at which the palm cannot extract water from the soil quickly enough for transpiration to continue at the potential rate. The palm will then start to suffer from water stress, and the 'plant water potential' will decrease. This will have direct effects on dry matter production, as the stomata will close, reducing photosynthesis, and it will also affect future yield, through effects on bunch number (Sections 4.4.4 and 4.4.5). Yield responses to irrigation, and the critical soil water deficit at which palm functions start to suffer, are discussed in Chapter 10.

Interactions between water deficit and other factors may occur. In the very dry climate of Benin, mortality of young palms during the dry season was greater at a planting density of 164 palms/ha than at 100 palms/ha (Djegui *et al.*, 1989). Mortality was also greater with a cover crop than where bare soil was maintained (Ochs and Daniel, 1976). Clearly, competition for water, either between palms, or with the cover crop, can be important.

4.3.3.1 Light interception and water deficit

Drought does not have much effect on leaf area of mature palms. It may cause a transient delay in leaf opening, but any effect on light interception will be small. In young palms, in contrast, drought may slow down development, so that, at a given age, leaf area is smaller in stressed palms than in unstressed. Henson and Chang (2000) compared adjacent 'wet' (low-lying, high water table) and 'dry' (sloping, well-drained) sites in Malaysia, and found that in 2–4-year-old palms f was 15–22% higher on the wet site, but in mature palms (9–10 years old) there was no difference. As noted above with fertilisers, in mature palms f is already high, so even if there are increases in leaf area, these will have little effect on light interception.

4.3.3.2 Photosynthetic conversion and water deficit

Drought causes stomatal closure in most plants, thus restricting water loss and preventing desiccation; Rees (1958, 1961b) showed that oil palms are no exception to this. Because the stomata are the route for carbon dioxide uptake, as well as for transpiration, drought also reduces the rate of photosynthesis.

Smith (1989) showed that 'drought' affected palm seedlings in controlled environments in two distinct ways: the stomata closed when soil water was limited, but they also closed in dry air, even if soil water was adequate. Henson (1991a), Dufrene and Saugier (1993) and Ruiz Romero and Henson (2002) confirmed the

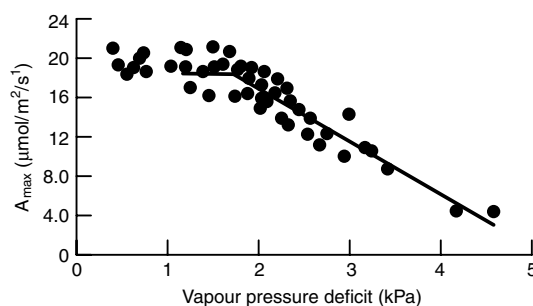


Fig. 4.9 Effects of vapour pressure deficit on light-saturated rate of photosynthesis. (From Dufrene and Saugier, 1993.)

effect of dry air on stomatal conductance of palms in the field.

Photosynthetic rate is not proportional to stomatal conductance at high conductances (stomata wide open), but below a certain threshold, as conductance falls, so does photosynthesis. Dufrene and Saugier (1993) found that $A_{\max}$ was independent of stomatal conductance and vapour pressure deficit (VPD) up to a VPD of about 2 kPa, but was reduced in direct proportion to VPD larger than this, as the stomata closed (Fig. 4.9). Following this work on individual leaflets, Henson (1995a) extended observations to the whole canopy, and showed that total daily photosynthesis also decreased in response to large VPD; this is illustrated in Fig. 4.10. On the first day of measurement, humidity remained high and carbon dioxide uptake exactly followed the hourly changes in solar radiation. On the next 2 days, large VPD developed and the maximum rate of carbon dioxide uptake was lower than on the first day, despite higher radiation levels.

Combining data from many days, Henson (1995a) showed that canopy photosynthesis was approximately halved when the largest daily VPD was 2 kPa, compared with VPD of 0.8 kPa or smaller (Fig. 4.11). The responses of total canopy photosynthesis to radiation and VPD were combined in a simple model, to predict photosynthesis from weather data (Henson, 1998b). In the comparison of wet and dry sites already mentioned (Section 4.3.3.1), Henson and Chang (2000) found that dry matter production was greater on the wet site, and in mature palms this was entirely due to greater e .

Henson *et al.* (1992) studied the effects of soil water deficit in more detail, growing nursery oil palm seedlings with their roots divided between two separate containers. If one half was droughted, abscisic acid levels rose, stomata closed and photosynthetic rate was reduced, and the rate of leaf opening was reduced,

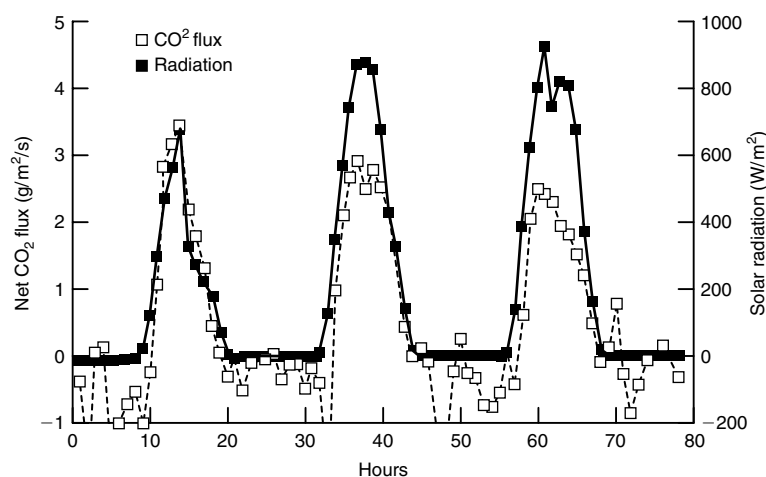


Fig. 4.10 Canopy photosynthesis measured by micrometeorology on 3 successive days. On day 1, photosynthesis closely followed total radiation, but on days 2 and 3, when there was a large vapour pressure deficit, photosynthesis was lower. (From Henson, 1995a.)

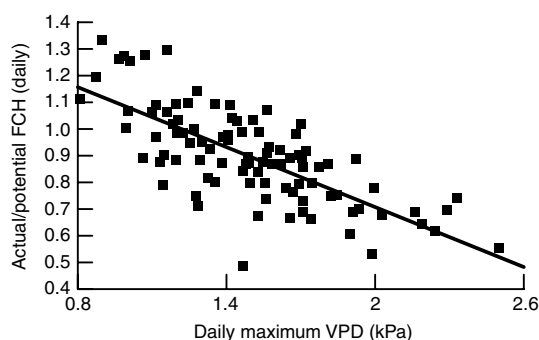


Fig. 4.11 Daily total canopy photosynthesis (FCH), decreasing with increasing vapour pressure deficit (from Henson, 1995a).

just as for fully droughted palms, even though leaf water potential, osmotic pressure and turgor pressure remained similar to fully watered palms. In a second experiment, after drying, the droughted half of the root system was cut off completely: stomatal conductance and rate of leaf opening then recovered to the level of the fully watered controls. Thus, for these seedlings, half the root system was able to supply sufficient water for the whole plant, but the other half appeared to send a signal that caused some of the visible or measurable effects of drought in the shoot. Similar behaviour has been recorded in other species (e.g. Tardieu, 1993). If the same mechanisms operate in mature palms, then irrigation methods that only wet some of the root system (e.g. drip) may be less effective than systems such as sprinklers that wet most of the area. Palat *et al.*

(2000) found no significant differences in yield between irrigation systems, however (see Chapter 10), and drip irrigation works well with other crops. Thus it remains to be confirmed what relevance the observations of Henson *et al.* have to mature palms.

4.3.3.3 Partitioning and water deficit

Water deficit may have some effects on vegetative growth. Henson and Chang (1990) showed that irrigation increased the annual rate of leaf production slightly in Malaysia. They also observed an increase in leaf dry weight under irrigation, and Desmarest (1967) observed increased rachis length and trunk basal diameter with irrigation in Ivory Coast. Much more important, though, are the effects of drought on bunch number: water stress causes inflorescence abortion, and also a reduction in sex ratio, both leading to lower bunch number. As discussed in Section 4.4, it is not clear whether these responses are a direct result of the reduced carbohydrate supply from photosynthesis during drought, or a consequence of changes in plant hormone status caused by drought, but the latter appears more likely.

Because of the time intervals between abortion or sex differentiation and harvest, a drought period causes reduced bunch number many months after the drought is over (Sections 4.4.4.3 and 4.4.5.2). As a result, as discussed in Section 4.2.2.3, there may be short-term discrepancies between assimilate supply and demand for bunch growth, with trunk storage probably providing the necessary buffering capacity. Over periods of months or years, yield in a seasonally dry climate is consistently lower than in a wetter climate.

4.3.3.4 Water use efficiency

For many crops, in environments where water supply is limiting, there is a linear relationship between dry matter production and the amount of water transpired. The slope of this line is the 'water use efficiency' (WUE), the amount of dry matter produced per unit of water transpired (although other definitions are sometimes used). Henson (1995a) estimated WUE of about 2.5 g dry matter (non-oil equivalent)/kg water transpired, for 10-year-old palms on a coastal site in Malaysia.

4.3.3.5 Waterlogging

Oil palms are well adapted to a high water table, but do not tolerate continuous waterlogging. Roots of most plants are unable to respire when submerged in water, and if flooding is prolonged, the roots may die. Water uptake may be impaired, with effects similar to those of drought (stomatal closure). Nitrogen uptake may also be limited, and waterlogged palms often appear nitrogen deficient. There have been few physiological studies of the effects of waterlogging on oil palm. Lamade *et al.* (1998c) showed that waterlogging caused root death in nursery seedlings, with stomatal closure resulting in reduced rates of photosynthesis and dry matter production.

4.3.4 Temperature

Low-temperature limits to oil palm growth are discussed in Chapter 3. As noted in Section 4.1.1.3, high temperatures are probably more often a limitation in most growing areas.

Leaves exposed to direct sunlight absorb energy. In well-watered plants this heating effect is countered, and leaf temperature is regulated, by the evaporative cooling of transpiration. Transpiring leaves are always cooler than non-transpiring leaves. Studies in many crops have shown leaf temperatures consistently below air temperature, but Hong and Corley (1976) found that leaf temperatures of well-watered nursery seedling oil palms were always above air temperature, sometimes by more than 10°C, except when the solar radiation level was below 350 W/m². They attributed this inefficient cooling to low wind speeds, and showed that wind speed and radiation accounted for 80% of the variation in leaf-air temperature difference (Δt) in nursery seedlings. They also found that leaf temperatures could be higher than air temperature in older palms in the field. Henson (1991b) confirmed the strong effect of radiation level on Δt , with leaf temperature above air temperature at radiation levels greater than 400 W/m², and Δt reaching 10°C at the highest radiation levels.

Rees (1961b) showed that oil palm stomata began to close when air temperature rose above 32°C. As air temperature rises, VPD increases, and oil palm stomata have been shown to close in response to increasing VPD (Section 4.3.3.2). Hong and Corley (1976) measured rates of photosynthesis at different leaf temperatures, and found an optimum at about 33°C, with much reduced rates at 40°C. Lamade and Setiyo (1996b) observed similar responses, but with clones differing in sensitivity to high temperature. However, Dufrene and Saugier (1993) showed that, provided that VPD was controlled so that stomatal closure did not occur, photosynthetic rates remained constant up to at least 38°C. Ruiz Romero and Henson (2002) confirmed this in Colombia. Thus, the inhibitory effects of temperatures between 33 and 40°C on photosynthesis may be largely due to VPD-induced stomatal closure.

4.3.5 Palm age

Changes in dry matter production and partitioning occur over the life of the plantation. The transition from immaturity to the mature fruiting stage, at about 2.5 years after field planting, has already been discussed (Section 4.2.2.1). Further changes also occur over the next 20 years.

4.3.5.1 Light interception and palm age

In mature palms at standard planting densities, f is typically 0.85 or higher, but averaged over the 25-year life of a plantation, it is only about 0.75 (Squire and Corley, 1987). This is because leaf area does not reach a maximum until about 10 years after planting (Hardon *et al.*, 1969). There is, therefore, scope for improving f by increasing ground cover by the canopy in the early years (Section 4.3.8.1). High planting densities give better early ground cover, but at the expense of later yield (see Chapter 9).

Breure (1988b) studied changes in extinction coefficient with palm age, and found the highest values at about 10 years after planting. In plantations older than about 12 years, light penetration through the canopy appeared to increase, perhaps because accumulating differences in palm height give a deeper canopy; theoretically, the deeper the canopy for the same value of L , the better the light penetration.

4.3.5.2 Photosynthetic conversion and palm age

Rees (1963a) pointed out that, as an oil palm stand ages, an ever-increasing proportion of the biomass consists

of living and respiring trunk tissue; he suggested that the respiratory load of trunk maintenance would increasingly tend to balance photosynthesis, leading to declining vigour and increasing disease susceptibility. If this were the case, declining e and yield would be expected after a certain age, but in well-managed plantations no marked yield decline is seen, at least up to the normal replanting age of 25 years (e.g. Lim and Chan, 1998), and Squire and Corley (1987) found no evidence for declining e with palm age (but see Section 10.7.3).

Breure (1988a) estimated total canopy photosynthesis from a model, and carbohydrate requirements for growth from Penning de Vries' figures (1972) and growth measurements, and assumed that the difference represented maintenance respiration. This did not increase indefinitely with age, as Rees had suggested, but appeared to stabilise at about 6 years after planting. Breure suggested that this was because most of the trunk is inactive, and respire very slowly; the active part is restricted to the youngest part of the trunk, with a fairly constant volume, independent of palm age (Breure, 1988a; van Kraalingen *et al.*, 1989). Henson and Chang (2000) have produced evidence to support this, finding much higher respiration rates (up to 10-fold) in trunk tissue samples taken from immediately below the apex than in samples from lower down.

4.3.5.3 Partitioning and palm age

Trunk height and total standing biomass increase steadily with palm age but, as noted above, this does not appear to result in an ever-increasing respiratory load. Leaf production rate remains fairly constant after about 10 years. Leaf area is more or less constant from 9–10 years onwards (Hardon *et al.*, 1969; Corley and Gray, 1976a), but information on leaf dry weights beyond 10 years is quite limited. Corley and Gray (1976a) showed petiole cross-section still increasing up to 20 years, but despite the correlation between petiole cross-section and leaf dry weight (Section 4.1.3.2) it seems unlikely that leaf weight continues to increase. If it did, this would mean that a declining surplus of assimilates would be available for bunch production but, as already noted, there is no good evidence for declining yield with age.

4.3.6 Pruning and defoliation

Under normal conditions senescent leaves are removed in regular pruning rounds, once or twice per year, but green leaves should not be pruned. However, when

bunches are harvested, it is usually necessary to remove one or more green leaves to gain access to the bunch stalk. Conventional pruning of mature palms typically results in leaf numbers between 32 and 40/palm, although lower numbers may occasionally be found.

Leaf-eating pests can cause severe defoliation. This is usually more or less randomly distributed through the canopy (although certain pests may concentrate on younger or on older leaves), but the effects of such defoliation are probably quite well simulated by complete removal of a proportion of leaves (severe pruning).

4.3.6.1 Light interception and pruning

Pruning inevitably reduces light interception, but the effect may be quite small. Corley (1976c) showed that pruning a stand of 138 palms/ha from 40 leaves/palm to 32 reduced L from 5.3 to 4.6. With an extinction coefficient, k , of 0.47 for PAR, and $a = 0.3$, Equation 4.11 predicts f of 0.9 and 0.87 for these L values. Severe defoliation has larger effects. With 24 or 16 leaves per palm, L was reduced to 3.5 or 2.3, and f would be 0.78 or 0.61.

4.3.6.2 Photosynthetic conversion and pruning

Oil palm leaves are long lived, compared with those of many crops. The leaves at the base of the canopy may have expanded more than 18 months earlier. Corley (1983a) showed that leaves up to 21 months old were still photosynthetically active, and this has been confirmed by Dufrene and Saugier (1989, 1993). Henson (1991c) found that the lower (older) leaves had a lower light compensation point and dark respiration rate, and lower $A_{\max}$, than upper leaves. This adaptation of older leaves to the shaded conditions is an important point when considering pruning regimes. It has sometimes been suggested that heavily shaded leaves at the base of the canopy may respire more than they contribute by photosynthesis, but Henson estimated that the oldest leaves would have a positive carbon balance under all but the most extreme conditions of high L and low PAR, so removing them is likely to reduce dry matter production and yield, even if only slightly.

After severe defoliation of young palms, Henson (1990b) showed that photosynthetic rate of the remaining leaves was increased. As noted in Section 4.2.2.1, this suggests feedback control of photosynthetic rate by sink demand, and if it is a normal occurrence, it would mean that the effects of defoliation on dry matter

production may be rather less severe than would be expected from light interception alone.

4.3.6.3 Partitioning and pruning

Corley (1976a) showed that, although severe pruning reduced VDM by 4%, leaf production rate was 7% higher in pruned palms. Wood *et al.* (1973) and Liao and Ahmad Alwi (1995) also observed increases in leaf production rate after defoliation. Severe pruning has some effect on leaf size; Corley (1976a) observed a 9% reduction in leaf dry weight, but a negligible effect on leaf area.

Despite these small changes in vegetative growth, the main effect of severe defoliation is as predicted by the overflow model: dry matter production is reduced, because of reduced light interception, and the reduction is almost entirely at the expense of bunch production. Effects of defoliation by pests are discussed in Chapter 12.

4.3.7 Inflorescence removal

Removal of inflorescences from young palms, variously known as disbudding, castration or ablation, is sometimes practised. The aim is to stimulate vegetative growth, and particularly root development in dry climates. A 'flush' of bunch production usually follows when disbudding has stopped, but in favourable climates, the loss of yield if disbudding is continued for too long may not be recovered in the flush.

4.3.7.1 Light interception and inflorescence removal

Disbudding for an extended period caused a small increase in leaf area (Corley and Breure, 1992). This would result in greater light interception (Table 4.3), but is unlikely to be important in practical terms.

4.3.7.2 Photosynthetic conversion and inflorescence removal

Removal of inflorescences, by removing a major part of the demand for assimilates, may lead to a reduction in photosynthetic rate (see Table 4.3). The aim of stimulating vegetative development may be achieved (see below), but the yield loss would only be recovered in the subsequent flush if photosynthesis continued at the normal rate, and the surplus carbohydrate was stored in the trunk. As noted in Section 4.2.2.2, in young palms the trunk is not large enough for this.

4.3.7.3 Partitioning and inflorescence removal

When yield was reduced by removal of 75% of inflorescences, VDM increased (Corley and Breure, 1992), but a 45% reduction in yield was associated with only a 5% increase in VDM. Removal of all inflorescences resulted in a 22% increase in VDM. Leaf production, leaf dry weight and area, and trunk diameter and height were all increased (Bénard and Daniel, 1971; Corley and Breure, 1992), and the basal bulge of the trunk is particularly marked where disbudding has been done.

Most importantly, the root system is more extensive in disbudded palms, and this can result in improved drought tolerance. The weight of roots was doubled by disbudding to 42 months after planting (Bénard and Daniel, 1971), and stomatal closure occurred later in the dry season and was less pronounced in disbudded palms.

4.3.8 Genetic variation

The non-destructive methods for estimating dry matter production were originally developed as a breeding tool, and it was shown that there were large and heritable differences between palms in partitioning of dry matter (Corley *et al.*, 1971b; Hardon *et al.*, 1972). Corley *et al.* (1971b) showed that if selection was based solely on yield per palm, there was a tendency to select tall, vigorous palms, which in part yielded well at the expense of their neighbours, and which might be expected to perform less well in a more uniform population. By using growth measurements, and selecting for high bunch index (improved partitioning to fruit), less competitive palms could be identified, which should give as good or better yields in a uniform stand. Hirsch (1980) confirmed the earlier work, showing that yield of individual palms was positively (although not significantly) correlated with palm height; those palms which overshadow their neighbours tend to have higher yields. In contrast, yield of plots of single families was negatively correlated with height. Within a family, height may be quite uniform, and when there is no competition with taller palms, the families that are less vigorous vegetatively have more dry matter available for bunch production. Since this work was done, clonal propagation methods have been developed (see Chapter 6), so the importance of performance in a uniform stand has increased.

Table 4.4 shows data for three contrasting clones in Indonesia, studied by Lamade and Setiyo (1996b). The vegetative measurements show that clone MK10 was

Table 4.4 Dry matter production for three contrasting clones in Indonesia.
Data from Lamade and Setiyo (1996b), except where indicated by comments

	Clone			Comments
	MK10	MK22	MK04	
Mean leaf area (m ²)	8.2	5.9	5.6	
Rachis length (m)	5.2	4.8	4.6	
Trunk height (m)	1.65	1.49	1.50	
LAI	7.09	4.47	4.02	Measured with PCA-2000 (Section 4.1.3.1)
<i>f</i>	0.96	0.86	0.83	Estimated from Equation 4.11
Yield FFB (kg/palm)	167	221	247	
Y* dry matter (kg/palm)	134	178	199	
Y* DMP (t/ha) (135 palms/ha)	18.1	24.0	26.8	
Trunk DMP (t/ha)	6.6	6.0	6.0	From biomass/3: palms 5 years old
Root DMP (t/ha)	3.0	1.7	1.8	From biomass/3
Leaf DMP (t/ha)	20.7	12.0	11.1	From biomass/2
Total* DMP (t/ha)	48.5	43.7	45.8	
BI* (%)	37.5%	55.0%	58.6%	
<i>e</i> * (g/MJ PAR)	0.90	0.91	0.99	PAR for 1994 = 5581 MJ/m ²
<i>A</i> _{max} (μmol/m ² per second)	30	31.6	27.4	
Respiration (μmol/m ² per second)	1.59	2.09	1.7	
Quantum yield (mol/mol)	0.068	0.071	0.082	
VPD sensitivity (regression)	−6.5	−9.78	−5.83	Slope of photosynthesis – VPD response (from Lamade and Setiyo)

The clones were planted in 1990, and measurements made in 1994.

*Adjusted for energy content of oil, assuming 25% oil/bunch.

much more vigorous than the other two. The highest FFB yield was obtained from clone MK04.

4.3.8.1 Genetic variation in light interception

Table 4.4 shows that clones that differ in vigour also differ in *L* and *f*, when compared at the same planting density. Gerritsma (1988) found no difference in extinction coefficient between different progenies derived from two different *pisifera* origins; nor did Corley and Donough (1992) find significant differences between clones. However, Lamade and Setiyo (1996a) found a large difference between two contrasting families in Indonesia (0.46 for one, 0.39 for the other). Thus, there may be scope to improve light distribution through the canopy by selection.

Breure (1985) showed that there was considerable variation between individual palms in the rate of increase in leaf area with age, and hence in the age at which maximum leaf area was reached. Squire and Corley (1987) estimated that for Breure's palms with rapid leaf expansion, *f* would reach 0.9 by about the fourth year after planting, 5 years earlier than for those with slow expansion.

4.3.8.2 Genetic variation in photosynthetic conversion

Gerritsma (1988) showed significant differences between progenies in *A*_{max}, and Smith (1993a) found low, but significant heritabilities for stomatal conductance and *A*_{max}. Lamade and co-workers (Lamade *et al.*, 1996a; Lamade and Setiyo, 1996b) found significant differences in *A*_{max} between clones. However, the clone with the highest *A*_{max} did not have the highest value for *e* (see Table 4.4); nor did respiration follow the same trend as *e*. Quantum yield (a measure of the efficiency of photosynthesis at low light intensity) appeared more closely related to *e*, although a conclusion cannot be based on only three clones.

Lamade and Setiyo also showed that clones differed in their sensitivity to VPD (Lamade and Setiyo, 1996b; Setiyo *et al.*, 1996). For all three clones studied, *A*_{max} decreased in direct proportion to VPD, but the slope of the line differed between clones (see Table 4.4), with photosynthesis falling to zero at a VPD of 4 kPa for the most sensitive clone, MK22, while clones MK10 and MK04 still had measurable (but low) photosynthesis at 5 kPa.

Corley and Lee (1992) considered that the major physiological change brought about by selection has

been to increase e . Smith (1993b) found differences in e between families of modern planting material, and Table 4.4 suggests differences between clones, so there would appear to be scope for further improvement. However, if feedback control of photosynthetic rate occurs (Section 4.2.2.1), it may confound attempts to compare photosynthetic rates of different genotypes, particularly at the nursery stage (e.g. Corley *et al.*, 1973b).

4.3.8.3 Genetic variation in partitioning

As noted above, the non-destructive methods for estimating dry matter production were developed because it was thought that there might be variation in partitioning, which could be utilised in a breeding programme. Corley *et al.* (1971b) and Hardon *et al.* (1972) confirmed the existence of significant genetic variation. Rees (1963a) pointed out that yield of oil palms might be increased in two ways: by increasing total dry matter production, with a constant fraction going to bunches, or by increasing the fraction going to bunches. The overflow model predicts that, if total dry matter production is increased, this is likely to increase the proportion of dry matter going to bunches. Corley and Lee (1992) showed that this is what has happened as a result of selection. Increases in e have increased total dry matter production, but as vegetative requirements have remained more or less unchanged, that has meant more dry matter available for bunches.

A comparison of clones MK04 and MK22 in Table 4.4 shows a similar result. The clones were similar in vegetative vigour, but clone MK04, with the higher value of e , had a greater excess of dry matter available after vegetative requirements were met, and gave a larger yield. Clone MK10 was much more vigorous; with a large leaf area, it had the highest light interception, but e was low, and the large requirement for vegetative dry matter meant that yield was much lower than for the other two clones.

Ruer (1967a) found that 'interorigin' *teneras* had a greater dry weight of roots than Deli *duras* in the same environment, and Lamade and Setiyo (1996a) found differences between families. These findings suggest the possibility of selecting for size of root system.

4.4 FLOWERING

Changes in FFB yield are always due to changes in one or other of the yield components, bunch number and bunch weight, so understanding the effects of environment on these components should help in explaining yield fluctuations. This will be important for successful

yield forecasting (Section 4.5.4). Typically, bunch number is more variable than mean bunch weight. Annual yield cycles are primarily due to changes in bunch number, as are differences between environments. For example, Henson (1998a) found that FFB yield was 35% greater on a wet than a dry site in Malaysia, and this difference was entirely due to differences in bunch number. Mean bunch weights were almost identical, age for age, on the two sites.

Bunch number and bunch weight can both be broken down into a number of subcomponents: leaf production rate, sex ratio, abortion rate and bunch failure rate for bunch number; spikelet number, flowers per spikelet, fruit set, weight per fruit and weight of stalk (or frame) for bunch weight. Study of the yield components, and of inflorescence development, started in the early days of oil palm research (Beirnaert, 1935b; Broekmans, 1957b; Henry, 1960; Sparnaaij, 1960). The main objective of most studies has been to understand yield fluctuations. An annual bunch number cycle is observed in all environments, although it is much more marked in some than in others. However, it is worth noting that, when the behaviour of individual palms is studied, it is difficult to distinguish regular cycles. The duration of sequences of female inflorescences, for example, appears more or less random, even in a strongly seasonal climate (Hemptonne and Ferwerda, 1961; Corley, 1977b). Haines and Benzian (1956) suggested that periods of 5 months predominated, but gave no data to support this. Henry (1960) pointed out that, in palms with the same average sex ratio, the duration of the sex phases may be widely different. This irregularity of individual palm behaviour accounts for some of the difficulties found in trying to understand the behaviour of populations of palms.

Lim and Chan (1998) found that bunch number per palm per year decreased steadily with age, from a peak of 28 bunches 5 years after planting, to fewer than eight bunches per year 25 years after planting. Mean bunch weight increased over the same period from less than 10 to 27 kg.

Various treatments have been used in studies of inflorescence development and yield components, most being aimed at modifying the carbohydrate balance between source and sink. Heavy pruning and high-density planting result in low source activity, while thinning a high-density planting, or pruning of neighbouring palms, leads to an abrupt increase in source activity. Partial or complete inflorescence removal changes sink demand. There have been few studies of inflorescence development in fertiliser or irrigation trials, however, and the way in which fertilisers influence yield components is not well understood.

4.4.1 Stages in inflorescence development

The development of the inflorescence is illustrated in Chapter 2, with extracts from the work of van Heel *et al.* (1987). As noted there, there is an inflorescence primordium in the axil of every leaf, and it is often more convenient to count leaf axils rather than inflorescences. The sequence of developmental stages, and approximate timings before anthesis, are shown in Fig. 4.12. The numbering of stages in this diagram follows Corley (1976d). The times of sex differentiation and of inflorescence abortion have attracted much attention, from the point of view of yield forecasting. As described in Section 4.4.5.2, the time of abortion is quite easily determined, but the time of sex differentiation has proved more difficult to define.

Broekmans (1957b) made the point that inflorescences reach the flowering stage in approximately the order that they were initiated, so will also have passed the stage of sex differentiation (and every other stage in development) in the same order. Thus, the time of the response of a yield component to an external stimulus may be determined by recording the yield component carefully, but the result may be specific to the environment or genotype studied. Corley (1976d) found a time lag from thinning a high-density planting until a change in sex ratio at anthesis of 17 months in one trial and 20 months in another. Turner (1977) observed effects of drought on yield, assumed to be due to change in sex

ratio, ranging from 21 to 26 months later (equivalent to 16–21 months to anthesis, which is about 5 months before harvest). There are at least two factors involved in this variation in the time lag: there are differences both in the number of unopened inflorescences in the growing point and also in the rate of opening. Dissection studies in different environments have shown large differences in the number of leaf primordia (see Section 4.4.3.2). The number of leaf primordia also varies among palms in the same environment; Corley *et al.* (1995a) found significant differences between clones. There were also differences between clones in the rate of leaf opening; these two factors combined led to a range of 11 months between the fastest and slowest clones, for the time from inflorescence initiation (stage 0) to anthesis (stage 8). For later stages in development, the range was smaller, with variation of less than a month between leaf opening and anthesis.

This variation in rate and timing of development, even within a population in the same environment, suggests that it may be difficult to detect clear responses of yield components to environmental factors.

4.4.2 Fruiting activity

The concept of fruiting activity is important for understanding oil palm yield cycles. Broekmans (1957b) introduced the term, referring to the number of bunches between anthesis and ripeness at any given time: before a period of high yield, there will be many bunches developing and demand for assimilates will be high. Broekmans suggested that abortion rate was higher during periods of high fruiting activity, and he also suggested that the yield cycles observed by Haines and Benzian (1956) and Haines (1959) might result from an effect of fruiting activity on sex differentiation.

4.4.2.1 Definition

An attempt to quantify fruiting activity was made by de Berchoux and Gascon (1965), who showed a correlation of abortion rate with the final weight of those bunches which were between anthesis and 3 months after, at the time of abortion. Corley and Breure (1992) calculated numerical values for fruiting activity from the estimated dry weight of all bunches developing on the palm in a given month. Dry weights were taken from Corley (1986) (Fig. 4.7), to give the following formula:

$$EA_n = 0.41 Y_{n+1} + 0.32 Y_{n+2} + 0.23 Y_{n+3} + 0.14 Y_{n+4} + 0.05 Y_{n+5} \quad (4.12)$$

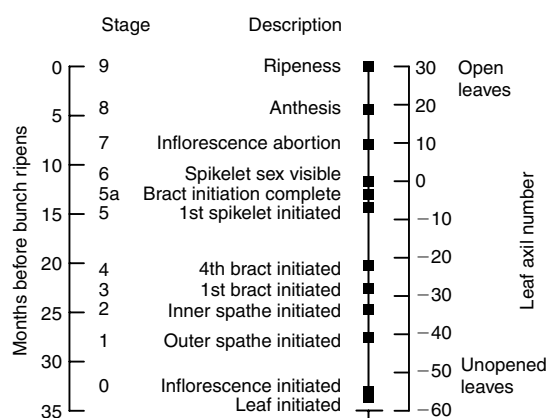


Fig. 4.12 Stages in inflorescence development. The right-hand scale gives leaf axil numbers (youngest fully open leaf = 1; unopened leaves have negative numbers), and the left-hand scale gives approximate times in months before harvest. Stages 4, 5, 5a and 6 are illustrated in Plate 2.6. (From Corley *et al.*, 1995a.)

where Y_n is the actual yield (fresh weight) in month n , and FA_n is fruiting activity. Fruiting activity is thus defined in terms of the amount of dry matter already incorporated in developing bunches, calculated from harvest in subsequent months. Corley and Breure (1992) pointed out that this does not necessarily imply direct effects of assimilate demand on yield components; effects of fruiting activity might be mediated through plant hormone levels.

4.4.2.2 Effects of fruiting activity

As noted above, de Berchoux and Gascon (1965) showed a correlation of abortion rate with fruiting activity. Corley and Breure (1992) and Breure and Corley (1992) showed effects of fruiting activity on bunch number (sex ratio, abortion rate and bunch failure rate), bunch weight and vegetative growth parameters (leaf size, leaf production rate and trunk growth). The effects on yield components are discussed in more detail in later sections. At this stage it may be noted that effects of fruiting activity can lead to negative feedback oscillations and endogenous yield cycles: high fruiting activity causes high abortion rate, and hence low bunch number and low fruiting activity, which in turn result in low abortion rate, and so on.

4.4.3 Inflorescence initiation

Each leaf axil contains a single inflorescence primordium. This may be male or female, and it may abort, but the rate of leaf production sets an upper limit to bunch number. The rate of initiation of inflorescences cannot be observed directly, but in published dissection studies an inflorescence primordium was always found within three or four leaf axils of the apical meristem. It thus appears that the rate of inflorescence initiation is the same as the rate of leaf initiation.

4.4.3.1 Rate of initiation

The rate of leaf initiation, as observed at the time of leaf opening, may be as high as 40/palm per year 2 years after planting, but it declines steadily with age, stabilising after 10–12 years at about two new leaves/month (Section 4.2.1.1). This monthly figure is not constant, though: Broekmans (1957b) and Ochs (1963) showed that leaf opening slowed down or stopped during the West African dry season, with a flush of leaves opening as soon as the rains started. Corley and Hong (1982) and Henson and Chang (1990; see also Henson, 1991a) observed higher leaf opening rates in irrigated

palms than in unirrigated during dry periods in Malaysia. Broekmans (1957b) showed that the rate of leaf development was probably not much affected by drought until about leaf -10 to -7 , when rapid elongation starts. Elongation is slowed down by drought (Henson, 1991a), as is leaf opening, so unopened spear leaves accumulate.

Chang *et al.* (1988) found little difference in the seasonal pattern between irrigated and unirrigated palms (irrigated palms produced about 0.06 more leaves/month than unirrigated), but there was only one severe dry period during their study. Despite the lack of significant drought, they found rates of leaf opening varying at different times from 1.5 to 2.5 leaves/month. Breure (1994) found rates varying from 1.3 to 2.9 leaves/month in Papua New Guinea. Corley and Breure (1992) found that the rate of leaf production was affected by fruiting activity; this may partly explain the fluctuations seen in the absence of drought.

The implication of relatively constant annual leaf production in different environments (Section 4.2.1.1), combined with short-term variability, is that the speed of leaf development may change, but leaf initiation rate is constant. However, where differences in annual leaf production persist over long periods, they must be accompanied by a difference in initiation rate. Breure (1994) found that thinning a high-density planting increased the rate of opening of new leaves, by 15% over a 46-month period. He considered the possibility that this change might have resulted solely from faster leaf development, without change in initiation rate. In that case, there would be a reduction in the number of leaf primordia in the bud, but the number of primordia was significantly higher in palms planted at very low density (56 palms/ha) than at normal densities. Further, the increase in rate of opening persisted up to 46 months after thinning, and was greatest from 24 months onwards. These results show, therefore, that thinning of a high-density planting increases the rate of leaf initiation, and hence also the rate of inflorescence initiation.

It is not known whether there is short-term fluctuation in the rate of initiation, which might contribute to short-term changes in bunch number.

4.4.3.2 Time of inflorescence initiation

The total number of leaf and inflorescence primordia found in the apical bud in dissection studies varies considerably (see Chapter 2 for a description of the apical bud). Brédas and Scuvie (1960) found nearly 60 unopened leaves in a 19-year-old palm in Congo. With a ripe bunch in the axil of leaf 28, and assuming production of two leaves per month, this indicates a time

from leaf initiation to harvest of about 44 months. Henry (1960) obtained very similar results in the Ivory Coast: 57 unopened leaves, corresponding to about 44 months before harvest. In the Far East, the number of primordia usually seems to be fewer: Corley (1976d) found a range from 41 to 54 primordia, and an estimated time ranging from 30 to 44 months, with an average of 36. The time interval was negatively correlated with rate of leaf production, and positively with palm age. Corley *et al.* (1995a) found a range for different 9-year-old clones of 50–62 inflorescence primordia, and times from initiation to harvest of 26–37 months.

4.4.4 Sex ratio

Oil palm inflorescences can be either male or female (or, occasionally, mixed; see Section 2.2.2). The sex ratio, defined as the ratio of females to total inflorescences, is an important factor in the seasonal variation of bunch numbers, but attempts to study sex differentiation are bedevilled by the fact that inflorescence abortion may not affect both sexes equally (Section 4.4.5.3). Thus, an apparent change in sex ratio may actually be due to a change in abortion rate, together with preferential abortion of females. To resolve this problem, Corley (1976d) used the number of male flowers, as a percentage of total leaf axils, as an indicator of true sex ratio. In effect, this is making the extreme assumption that all aborted inflorescences are female, but if abortion is not always preferential, as Breure and Menendez (1990) indicated, then true changes in sex ratio could sometimes be missed.

Corley and Gray (1976b) showed the sex ratio diminishing with age from 90% at 4 years after planting to under 60% at 15 years on coastal soils in Malaysia. On inland soils, the sex ratio was about 70% at 3 years and 40% at 15 years. In Nigeria, Sparnaaij (1960) recorded 47% at 5 years, but 30% or below from 10 years onwards. These figures are no more than an indication, given the effects of environmental factors discussed below, together with genetic variation (Sparnaaij, 1960).

4.4.4.1 Factors affecting sex ratio

Beirnaert (1935b) was one of the first to look at sex determination in the oil palm. He considered that the sex ratio depended on the ratio of carbon assimilation to mineral absorption by the palm. Broekmans (1957b), Sparnaaij (1960), Sparnaaij *et al.* (1963b) and others accepted this hypothesis. Sparnaaij took 'mineral absorption' to mean nitrogen, and found a negative correlation between soil nitrogen and sex ratio in one trial.

Moisture deficit during the dry season was thought to be important, because radiation would be less effective during periods of drought, but the primary factor influencing the sex ratio was thought to be radiation, through its influence on carbohydrate status.

More recent work has emphasised the importance of water stress. In Ivory Coast, irrigation caused a reduction in male flower number per palm, indicating an effect on sex differentiation (IRHO, 1970). Corley and Hong (1982) similarly observed increases in sex ratio in response to irrigation. High male flower production and low yield are regularly observed after a drought (e.g. Turner, 1977). In Ecuador, with irrigation, FFB yields of over 28 t/ha have been achieved, despite only 870 sunshine hours/year (Mite *et al.*, 2000), suggesting that factors such as water supply and atmospheric humidity may be more important than radiation level.

An effect of water stress on the sex ratio is not, of course, inconsistent with Beirnaert's hypothesis; the reduction in photosynthesis caused by water stress (Section 4.3.3.2), will tend to lower the carbohydrate status of the palm. Other factors affecting the sex ratio also fit with Beirnaert's hypothesis. Defoliation, and intense competition for light in high-density plantings, both reduce dry matter production per palm, and also cause reductions in sex ratio (Sparnaaij, 1960; Corley and Hew, 1976; Breure and Menendez, 1990; Corley *et al.*, 1995a; see also Section 9.3), while a reduction in fruiting activity, by removal of developing inflorescences, caused an increase in sex ratio (Corley and Breure, 1992). *Pisiferas* have a consistently high sex ratio (Broekmans, 1957b; Sparnaaij, 1960), associated with bunch failure and hence low fruiting activity. Broekmans (1957b) and Sparnaaij (1960) also stated that *tenera* palms tended to have a slightly higher sex ratio than *duras*, but no comparison of different fruit types in the same family appears to have been made.

Sparnaaij (1960) pointed out that, under Beirnaert's hypothesis, an improvement in mineral absorption, without change in carbohydrate status, as might occur following fertiliser application in a light-limited situation, should result in a lower sex ratio, but no convincing evidence for such a response has been published.

4.4.4.2 Mechanism of sex determination

If yield is source limited (which is not entirely clear; see Section 4.2.2), there must be some mechanism whereby carbohydrate supply influences yield. Whether this is through a direct effect on sex differentiation, as Beirnaert supposed, or rather on hormonal status which in turn influences sex, is not certain, but it appears

probable that hormones are involved in the control of sex ratio. There are numerous examples of growth regulators (plant hormones) affecting flower sex, in many different species (Korpelainen, 1998), and effects of growth regulators on oil palm sex ratio have been demonstrated. Corley (1976b) showed that the application of gibberellic acid increased male inflorescence production; conversely, Hashim (1993) observed increases in female flower number and decreases in males following the application of paclobutrazol, an inhibitor of gibberellin synthesis (although the effects were not statistically significant). Huntley (1995) found more male flowers, and extracted higher levels of active gibberellins from inflorescence sap, in pruned than in unpruned palms. These results suggest that gibberellins are involved in the control of sex ratio. Absciscic acid (ABA) may also be involved. This compound is known to affect flower sex in other species (Korpelainen, 1998), and Henson *et al.* (1992) showed that ABA level increased in droughted oil palm seedlings. Effects of drought on gibberellin levels in oil palm have not been investigated.

4.4.4.3 Timing of sex determination

Broekmans (1957b), following Beirnaert's hypothesis (Beirnaert, 1935b) assumed that a high sex ratio originated during periods of high radiation and hence high carbohydrate status; under Nigerian conditions, this appeared to mean the dry season. From dissections, only the dry season 24 months before anthesis was considered feasible; at 36 months, the inflorescence had not been initiated, while by 12 months the sex was already visibly determined. Thus, sex differentiation was assumed to occur 24 months before anthesis, or 29–30 months before harvest. This was supported by correlation studies, but the correlations were between dry season rainfall and annual mean sex ratio, so could not give precise information on timing. Corley (1973a) noted that Broekmans' data showed regular peaks of male inflorescence production about 20 months after the dry season, so could be interpreted as indicating that drought causes a low sex ratio, not a high one. Sparnaaij (1960) recorded a change in sex ratio after 19–20 months following an increase in light by pruning of neighbouring palms in Nigeria, but interpretation of his results is complicated by the fact that pruning was repeated at the same time in 4 successive years. Sparnaaij *et al.* (1963b) observed a drop in sex ratio at 24–26 months after severe pruning, but the response was not very clear.

In Ivory Coast, Durand-Gasselin *et al.* (1999a) pruned *pisifera* palms to increase male inflorescence and pollen

production for breeding. In 14-year-old palms, male inflorescence numbers started to increase about 18–20 months after pruning. In 34-year-old palms, the response came about 4 months later, at 22–24 months.

Studies in the Far East have shown a wide range of response times. Effects of drought were seen ranging from 16 to 21 months before anthesis (Turner, 1977). Breure and Menendez (1990) found a response to thinning after about 14 months, and one of the clones studied by Corley *et al.* (1995a) showed a response as early as 11–13 months after pruning.

Because of the variation in times of response, Corley (1976d) tried to generalise, combining environmental manipulation with palm dissection, to relate the time of response in sex ratio to the developmental scale shown in Fig. 4.12. In a comparison of two thinning trials, he showed a divergence of several months in the actual time of response, but good agreement on the developmental scale. A change in sex ratio only occurred in inflorescences that had not passed stage 3 when thinning was done. Based on this finding, Corley used the results of several dissection studies to estimate that sex differentiation (i.e. stage 3) occurred, on average, 20 months before anthesis, or 25 months before harvest. The range was large, however: between 21 and 29 months before harvest. About 60% of the variation was associated with rate of leaf production.

More recent work has clouded the picture: Breure and Menendez (1990) adopted the same dissection technique, but obtained a different result: their data show a significant drop in male inflorescence number at leaf –11, approximately midway between stages 3 and 5. Corley *et al.* (1995a) used the same method to study effects of defoliation on oil palm clones, and found that clones differed in the stage at which responses occurred. In six out of seven clones there was a sex ratio change at stage 3, but in three clones there was also a change in a few leaf axils before stage 5 (Fig. 4.13).

In summary, these results suggest that there is not just one point in development at which sex is differentiated; sex is probably initially determined at about stage 3, but whatever occurs at that stage is not irreversible. Up to about stage 5, changes in carbohydrate status (pruning, thinning, fruiting activity) can still influence sex. Treatment effects have not been seen after stage 5, but it is possible that mixed inflorescences (Williams and Thomas, 1970) are the result of late changes. Thereafter, the inflorescence sex is fixed, but the proportions of males and females emerging may still be altered, if preferential abortion of one sex occurs (Section 4.4.5.3).

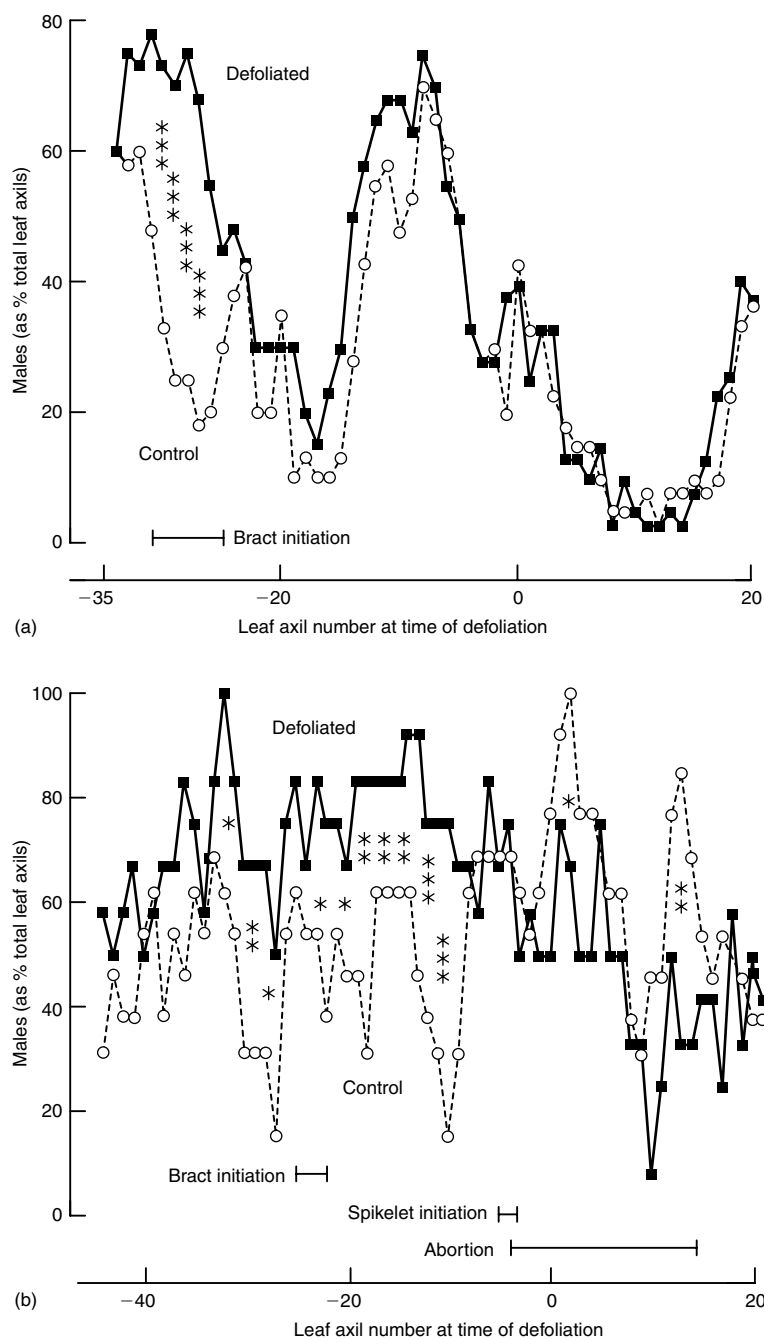


Fig. 4.13 Ratio of male inflorescences to total leaves for oil palm clones, with and without defoliation. Plotted against leaf axil numbers and developmental stages, determined by dissection at the time of defoliation. (a) Mean data for three clones, all showing a response at the bract initiation stage (stage 3 of Fig. 4.12); (b) data for a clone showing a response just before the spikelet initiation stage (stage 5 of Fig. 4.12). (From Corley *et al.*, 1995a.)

4.4.5 Inflorescence abortion

Inflorescence abortion is the second main factor determining final bunch number. Aborting inflorescences stop growing while still completely enclosed by the leaf

base, so they appear as empty leaf axils. Dissection always reveals a partially developed, and usually rotten, inflorescence in such empty leaf axils, however. In Nigeria, Sparnaaij (1960) recorded 24–28% abortion in

4–5-year-old plantation palms, diminishing to less than 10% by 11–12 years (aborted inflorescences as a percentage of total new leaves produced), but in grove palms abortion was much more significant, averaging 51% (Zeven, 1967). On coastal soils in Malaysia, Gray (1969) found abortion rates ranging from 2 to 28%, and averaging around 10%; there was a slight trend towards an increase with palm age.

4.4.5.1 Factors affecting abortion rate

Abortion rate appears to be influenced by the same factors as sex ratio. Broekmans (1957b) showed that peaks of abortion originated during the dry season in Nigeria, and Desmarest (1967) showed that irrigation reduced the abortion rate in Ivory Coast. Thinning a high-density planting reduced the abortion rate (Breure and Menendez, 1990), while severe pruning induced heavy abortion in six out of seven clones (Corley *et al.*, 1995a).

Although they are affected by the same factors, abortion rate and sex ratio appear not to have the same thresholds of response to stress: Breure *et al.* (1990) found that abortion was higher at 110 than at 56 palms/ha, whereas sex ratio was not significantly different between the two densities (see Section 9.3). Corley and Breure (1992) found that a 20% decrease in fruiting activity (from inflorescence removal) gave the maximum reduction in abortion rate, but further decreases gave progressively higher sex ratios. These results are contradictory, if considered in terms of carbohydrate availability or status: high density and heavy fruiting should both lower carbohydrate status, but abortion was more sensitive to increase in density, while sex ratio responded first to increased fruiting activity.

Ali Sekak *et al.* (1981) showed that a growth-retardant chemical (CF125, or 9-hydroxyfluorene-9-carboxylic acid methyl ester) could be used to induce abortion. The aim of this was to change the yield cycle caused by the effects of fruiting activity, and thus to gain some control over seasonal yield fluctuations. Corley and Teo (1976) had earlier shown that manual disbudding could change the seasonal yield pattern, with little loss of total yield. Ong (1982a) found a correlation between diurnal temperature range and yield 7–9 months later, suggesting a possible effect on abortion rate, but there are no other reports of effects of diurnal temperature range.

4.4.5.2 Timing of abortion

Broekmans (1957b) found, by dissection, that the inflorescence elongates slowly up to about leaf 7, then at

a much faster rate until just before anthesis. By comparing the size of aborted inflorescences with this growth curve, he deduced that abortion occurs approximately at the start of the second phase, in the axil of leaf 8 or 9 (Fig. 4.14). If an inflorescence survives beyond this stage, then abortion is very unlikely to occur later. Several dissection studies have confirmed Broekmans' findings (Henry, 1960; Corley, 1976d; Corley *et al.*, 1995a). Anthesis typically occurs in the axil of about leaf 19 in mature palms, so with two leaves opening per month, abortion occurs about 5 months before anthesis, or 10 months before harvest. Brédas and Scuvie (1960) stated that abortion occurred 19–20 months before harvest, and Turner (1977) suggested that drought might cause abortion at a similar stage. However, numerous manipulative experiments have confirmed that the time interval is 9–10 months, and abortion at an earlier stage has not been seen in any of the published dissection studies.

4.4.5.3 Sex of aborted inflorescences

Broekmans (1957b) pointed out that there are two ways in which the sex ratio of aborted inflorescences might differ from that of the total number of inflorescences. First, inflorescences of one sex may have a greater tendency to abort than those of the other. Secondly, peaks of abortion might occur at times when the sex ratio deviated from the annual mean. It is the first of these possibilities that has attracted most attention, but attempts to investigate this by looking at the sex of aborted inflorescences have not been very successful, because they rot quickly and become unrecognisable.

Corley (1973a, 1976d) found that severe defoliation caused abortion of female inflorescences, but not of males. This is shown in Fig. 4.15, where the number of females is significantly reduced between 4 and 9 months after pruning, while the number of males is unchanged. Breure and Menendez (1990), comparing thinned with unthinned palms, found that preferential abortion of female inflorescences was transient, with no difference in the ratio of males to females after the first 2 months. They speculated that the larger size of female inflorescences might make them more prone to abort at the onset of a period of stress, but in Corley's trial the preferential abortion continued for 6 months. Corley *et al.* (1995a) noted that abortion appeared to be preferential for females in one clone, but not in five others. Thus, it appears that, for reasons at present unknown, abortion is sometimes predominantly of female inflorescences, but not always.

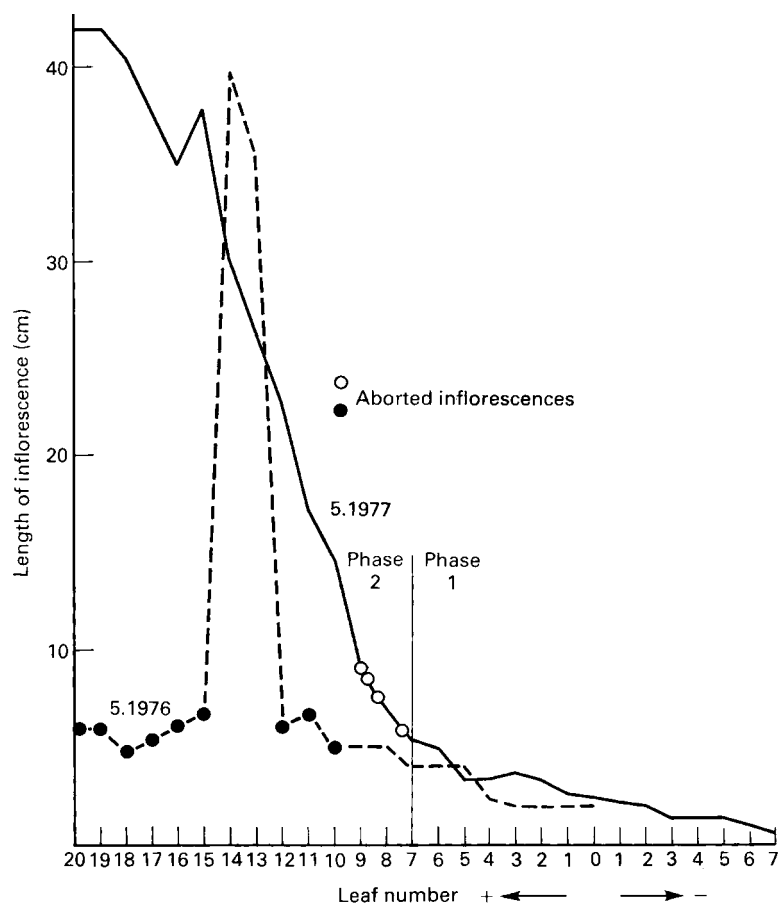


Fig. 4.14 Lengths of immature inflorescences. Data from two palms, showing that all aborted inflorescences are about the same size, corresponding to leaf axil 7–9. (From Broekmans, 1957b.)

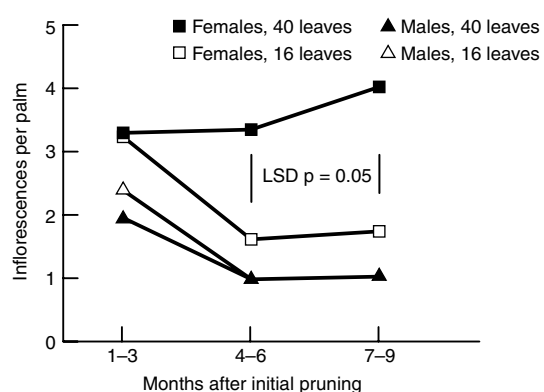


Fig. 4.15 Inflorescence production after pruning. The number of female inflorescences declined after pruning to 16 leaves per palm, from the normal 40 leaves, but the number of males remained unchanged. (From Corley, 1976d.)

4.4.5.4 Mechanism of abortion

Broekmans (1957b) suggested that abortion occurred because the tight enclosure of the inflorescence by the leaf base was a physical impediment to expansion. When the 'plane of nutrition of the palm is at a low level' the inflorescence is unable to overcome this, and 'first stagnates, and may finally abort'. The work of Chang *et al.* (1995) indicates that some degree of stagnation does occur: the period from emergence of the leaf to anthesis of the inflorescence in its axil varied by as much as 100 days, being longest for inflorescences immediately before and after periods of abortion.

Bealing and Haniff Harun (1989) calculated that production of carbohydrate by a single leaf was about three orders of magnitude greater than the requirement for inflorescence growth at the stage when abortion occurs, and Henson (1990a) showed that the carbohydrate

content of inflorescences with retarded growth was similar to, or greater than, that of normal inflorescences. Thus, it is unlikely that limited assimilate supply is the direct cause of abortion. Bealing and Haniff Harun (1989) speculated that abortion might occur because of localised water stress. However, they noted that aborting inflorescences had higher water content than normal inflorescences; this is one of several apparent flaws in their argument. They suggested that the volume of phloem sap required to transport sugar to developing bunches could lead to water stress, and hence the observed effects of 'fruiting activity'. However, the calculated volume of phloem sap was never more than a few per cent of the total water flow through the transpiration stream, so it seems unlikely that changes in phloem sap flow would have much effect. They found that inflorescences have a high proline content at the stage when abortion occurs, which they took to be a symptom of water stress, as they also showed that proline accumulates in droughted oil palm leaves. However, other factors also cause proline accumulation (e.g. low temperature: Tarmizi and Marziah, 1995), while Henson (1990a) found much lower proline levels in slow-growing than in normal inflorescences.

Bealing and Haniff Harun (1989) mentioned, but did not fully illustrate, some interesting anatomical studies of the development of the vascular system of the inflorescence. Some combination of mechanical restriction imposed by the leaf sheath, and nutrient or assimilate supplies limited by the lack of vascular connections, may well be the explanation for the critical stage in inflorescence development that occurs in the axils of leaves 8–10.

4.4.6 Bunch failure

Sparnaaij (1960) used the term bunch failure to describe bunches that fail to develop from anthesis to harvest, but some authors have, confusingly, used the term abortion, or late abortion, for this. We prefer Sparnaaij's usage. Sparnaaij observed an average of 13% bunch failure in 7–12-year-old palms in Nigeria, but Corley (1973a) found less than 2% in Malaysia. Frequencies may be higher in young palms: 28% between 4 and 6 years in Nigeria (Sparnaaij, 1960), and up to 25% in Malaysia in the third year after planting (Liau and Ahmad Alwi, 1995). Olivin (1966) observed seasonal variation in bunch failure rate in Benin.

There are several different causes of bunch failure. Poor pollination is one cause, but this has become rare since the introduction of pollinating weevils to all oil palm-growing areas (Section 4.4.7.1). Bunch rot may be caused by *Marasmius palmivorus* (see Section 12.1.8).

At times, though, bunches fail, 2–4 months after anthesis, for no obvious reason. Bunch failure occurs shortly before the maximum demand for assimilates builds up as oil synthesis starts, and Turner and Bull (1967) suggested that it may be caused by 'overbearing'. However, Corley (1973a) showed that pruning of 8-year-old palms, severe enough to cause abortion of 80% of inflorescences, had very little effect on bunch failure rate; almost all bunches which, at the time of pruning, had already passed the abortion stage subsequently developed to ripeness. This suggests that overbearing is not normally a major factor; bunch failure may be the response of 'last resort' to severe assimilate shortage.

4.4.7 Bunch weight

The weight of a bunch depends on the number of spikelets, the number of flowers per spikelet, the percentage fruit set, the mean weight per fruit and the weight of the frame (Broekmans, 1957b). Bunch weight increases steadily with age (Brédas and Scuvie, 1960; Corley and Gray, 1976b), up to at least 15 years after planting. For a sample of 11 palms, recorded continuously, Lim and Chan (1998) found bunch weight still increasing 26 years after planting. Palms at very low planting density (see Section 9.3) or with most inflorescences removed (Corley and Breure, 1992) develop greater bunch weights than under normal conditions, indicating that 'potential' bunch weight is not normally achieved.

Broekmans (1957b) noted seasonal fluctuations in bunch weight, related to spikelet number and flowers per spikelet, but variation in bunch weight is much less than in bunch number.

4.4.7.1 Fruit set

Bunch weight depends partly on fruit set, and thus on the efficiency of pollination. Wong and Hardon (1971) found significant correlations of bunch weight with fruit set and fruit to bunch ratio, in an experiment comparing different methods of assisted pollination. Their results are sometimes quoted as showing that above a level of fruit set of about 50% there is little further increase in fruit/bunch (F/B), because as fruit number increases, the size of individual fruits starts to decrease (Fig. 4.16a). This may be misleading: because the weight of fruit appears in both numerator and denominator of the F/B ratio, quite large changes in weight of fruit make little difference to the ratio. If, instead of F/B, we calculate the actual weight of fruit per bunch, this continues to increase up to higher levels of fruit set

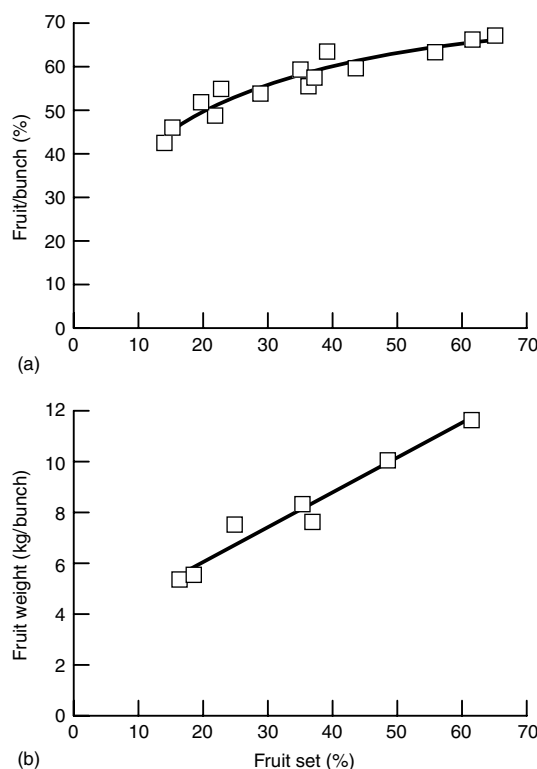


Fig. 4.16 Relationship between fruit set and fruit weight. Lines are fitted curves. (a) Fruit/bunch (%), showing a tendency to plateau at high fruit-set levels; (b) weight of fruit/bunch (kg), showing a more or less linear increase with increasing fruit set. (From data of Wong and Hardon, 1971.)

(Fig. 4.16b). It appears, therefore, that the assumption that 50% fruit set is optimal and 40% 'adequate' may be incorrect, and rather higher levels should be aimed for.

Until the late 1970s, it was generally believed that the oil palm was wind pollinated (e.g. Hardon and Corley, 1976; Turner, 1978). In parts of South-east Asia, assisted pollination was often found to be necessary to ensure good fruit set in young palms (Gray, 1966); this was attributed to lack of male flowers, low wind speeds and heavy rain. In Sabah and PNG, the need for assisted pollination continued throughout the life of the palm. Detailed accounts of methods of assisted pollination are given by Turner and Gillbanks (1974) and Speldewinde and Pereira (1974). As an alternative to assisted pollination, the possibility of using growth regulators to stimulate parthenocarpic (seedless) fruit production was considered (Chan, 1972; Thomas *et al.*,

1973). Although spraying with auxins could give completely parthenocarpic bunches, the missing kernels were not replaced by additional mesocarp, so the value of the bunches was reduced.

At various times it had been suggested that insects might be involved in pollination, but it was only in the late 1970s, in a research project instigated by L. Davidson, that Syed (1979) found that in Cameroon the oil palm was almost entirely pollinated by insects, not by wind (see Section 2.2.2.5 for more detail). In Malaysia, Syed found that *Thrips hawaiiensis* was the main pollinating agent, but this species was usually absent from young plantings, explaining why assisted pollination was needed. The pollinating weevil *Elaeidobius kamerunicus* was introduced to Malaysia in 1981 (Syed *et al.*, 1982). The initial effects of the introduction of *E. kamerunicus* to Peninsular Malaysia, where *T. hawaiiensis* was already present, are illustrated in Table 4.5. Increased fruit set resulted in higher F/B ratio, mean bunch weight and yields. The average fruit size was reduced, but the percentage of kernel to bunch was increased. Mesocarp/bunch and oil/bunch were increased in the younger palms, but not in the older.

The longer term effects of weevil introduction were described by Donough and Law (1988). They compared yields and bunch analysis data for periods of 4 years before and after *E. kamerunicus* release, both in Johore, Peninsular Malaysia, and in Sabah. Table 4.6 shows that the initial effects noted in Table 4.5 were maintained, but were more pronounced in Sabah than in Johore. In Johore, where *T. hawaiiensis* was present before the release of *E. kamerunicus*, the increase in bunch weight was offset by a reduction in bunch number, so that FFB yield remained unchanged. This presumably resulted from an effect of increased fruiting activity on bunch number components (Section 4.4.2). In Sabah, under assisted pollination, yields and mean bunch weights were lower than in Johore before the introduction. After the introduction, bunch weight increased, with relatively little reduction in bunch number. Presumably, in this situation, poor fruit set meant that yields before the release had not reached a level where assimilate supply or fruiting activity became limiting (see Section 4.2.2.1).

Following the release of *E. kamerunicus* in the Far East, some earlier observations on fruit set are no longer relevant. Corley (1973b) found no effect of plant density on oil/bunch, but recent work has shown that fruit set and oil/bunch are improved in high-density plantings, perhaps because *E. kamerunicus* is more active in the darker and cooler microclimate of the high-density canopy (Breure *et al.*, 1990).

Table 4.5 Effects of the introduction of *Elaeidobius kamerunicus* on bunch composition in Malaysia

Bunch component	6–8-year-old palms		15–22-year-old palms		10-year-old palms	
	Before	After release	Before	After release	Before	After release
Fruit set (%)	47.8	76.0	52.4	71.2	–	–
Fruit/bunch (%)	60.4	68.3	60.4	64.4	56.0	63.0
Mean bunch weight (kg)	10.7	13.6	23.5	26.9	15.2	19.8
Mesocarp/bunch (%)	46.2	51.1	45.2	45.5	46.4	50.4
Oil/bunch (%)	22.7	24.9	22.0	21.5	22.4	23.9
Kernel/bunch (%)	4.7	7.0	5.5	7.4	4.0	5.3
Samples analysed	351	220	200	200	–	–

Data from Syed *et al.* (1982) and Yee *et al.* (1985).

Table 4.6 Longer term effects of the introduction of *Elaeidobius kamerunicus* in Malaysia

Yield component	Kluang, Johor		Pamol, Sabah	
	Before 1977–1980	After release 1982–1985	Before 1977–1980	After release 1982–1985
Yield (t/ha per year)	23.3	23.9	16.9	20.8
Mean bunch weight (kg)	21.6	27.8	13.4	17.5
Bunch number (no./palm per year)	7.8	6.2	9.1	8.6
Oil extraction ratio (%)	20.6	20.3	20.0	21.0
Oil yield (t/ha per year)	4.8	4.9	3.4	4.4
Kernel extraction ratio (%)	6.0	7.1	4.1	4.7
Kernel yield (t/ha per year)	1.4	1.7	0.7	1.0

Data from Donough and Law (1988), for 1966–1968 plantings, 13–15 years old at time of introduction in 1981.

Although *E. kamerunicus* is now well established all over South-east Asia, instances of inadequate fruit set still sometimes occur (e.g. Donough *et al.*, 1996a; Rao and Law, 1998; see also Section 4.5.2). Some attempts have been made to define the minimum weevil population needed to ensure good fruit set. These have been rather inconclusive, partly because weevil population has been estimated in several different ways. The usual procedure is to collect a sample of spikelets from male inflorescences, early in the morning while the weevils are still inactive. The population per hectare can then be estimated from the number per spikelet, number of spikelets per inflorescence and number of inflorescences per hectare. However, Syed and Saleh (1988) found that estimates obtained in this way were inaccurate, and it was better to collect entire inflorescences. Other approaches have included the use of sticky traps to collect weevils as they visit female inflorescences, or the collection of samples of male spikelets with weevil larvae and pupae, the spikelets being stored until adult weevils emerge and can be counted.

Donough *et al.* (1996a) estimated that a population of about 20,000 weevils/ha was sufficient to ensure reasonable fruit set. In some studies, female inflorescences have also been counted, and the population available per female inflorescence has been estimated. Syed and Saleh (1988) considered that if the weevil population was less than about 700 per female inflorescence, fruit set might be inadequate. These figures are of a similar order, if one assumes one female inflorescence per palm per month, with anthesis lasting for about 4 days.

4.4.7.2 Other components of bunch weight

High planting density depresses bunch weight, through effects on spikelet number, flowers per spikelet and frame weight (Breure *et al.*, 1990). Severe pruning also depressed bunch weight (Corley and Hew, 1976). Fruiting activity influenced bunch weight, and an increase in weight followed removal of inflorescences (Table 4.3), with spikelet number, flowers per spikelet and frame weight all responding positively. Bunch weight is

strongly influenced by fertilisers, but which components are affected does not appear to have been studied.

4.4.7.3 Times of determination of bunch weight components

The times of determination of the various bunch weight components can, in principle, be ascertained by monitoring the effects of pruning, thinning and other treatments, just as for bunch number components. However, negative correlations between different components, and the fact that the changes in individual components are usually quite small, have made the results of some trials difficult to interpret.

Mean fruit weight: This component was depressed about 3–4 months after a severe pruning treatment (Corley, 1973a). In other trials, responses of mean fruit weight have not been very clear, and have sometimes been in the opposite to expected direction (e.g. a reduction following thinning: Breure and Menendez, 1990). Mean fruit weight and fruit set are usually negatively correlated, which may explain some of the difficulties (Broekmans, 1957b; Wong and Hardon, 1971).

Fruit set: This is determined at the time of pollination, between 5 and 6 months before harvest.

Flowers per spikelet: This component may be determined about 12–15 months before harvest (Corley, 1973a; Corley and Breure, 1992). However, Breure and Menendez (1990) found that the response to thinning was only seen in inflorescences that were at the leaf – 12 position at the time. This corresponded to about 14 months before anthesis, or 19 months before harvest.

Spikelet number: This component was depressed about 14 months after severe pruning (Corley, 1973a). However, when disbudding was stopped, Corley and Breure (1992) observed a change in spikelet number within 9 months. This would correspond to inflorescences in the axils of leaves 8–10, well after the point where dissection shows inflorescence structure to be fully differentiated. Breure and Menendez (1990) also observed a transient response at this stage. The most likely explanation for this is that it is related to preferential abortion of larger bunches; the response seen by Breure and Menendez coincided with a change in abortion rate.

Frame weight: Breure and Menendez (1990) found two responses of frame weight (bunch stalk and spikelets) to thinning, with increases at 7–9 months and 14 months before harvest, but Breure and Corley (1992) found no clear response.

Bunch weight: The range of different response times for the bunch components implies that bunch weight

should also be affected at several different stages. Surprisingly, though, the main effect of fruiting activity appears to be about 10 months before harvest, which does not correspond exactly to any of the components (Breure and Menendez, 1990; Breure and Corley, 1992). There is no obvious explanation for this response.

4.4.8 Rates of inflorescence and bunch development

The overall rate of bunch development parallels that of leaf development. An inflorescence primordium is initiated within a few leaf axils of the apical meristem, and the inflorescence anthesises at leaf 18–20, in a mature palm. Rates of leaf production are very similar in different environments (Section 4.2.1.1), implying similar rates of inflorescence development. Within this regular framework there may be some variation.

Breure and Menendez (1990) noted that, according to Henry (1960) and others, inflorescence sex was apparently distinguishable some ten leaf axils earlier in West Africa than in South-east Asia. If that is correct, then in Africa the early stages of development must be faster, and later stages slower, than in South-east Asia. This seems improbable, and it is more likely that different criteria have been used by different authors to judge the sex of a developing inflorescence.

Seasonal fluctuations in yield are undoubtedly largely caused by changes in climatic factors (Section 4.5.3), although the effects of fruiting activity on future yield components may perpetuate a yield cycle even in a relatively unchanging climate. There is, additionally, variation in the rate of bunch development, which can exaggerate the seasonal cycle. This was demonstrated by Olivin (1966), who studied yield components in Benin. He found that the time from leaf opening to anthesis varied during the year from 250 to 350 days, and the time from anthesis to ripeness varied from less than 150 to more than 175 days. These two factors, combined with delayed leaf opening during the dry season, resulted in the inflorescences subtended by leaves opening in the 8 months from September to April being harvested in 3 months between February and April in the following year. This concentration was a contributory factor in 60% of the annual yield being harvested in the 4 months from February to May. An additional factor was that bunch failure was only 3% from February to April, but 20% during the rest of the year.

Olivin's observations were made in a strongly seasonal climate, but bunch development rates can be quite variable even in a more uniform climate (Corley, 1977b; Chang *et al.*, 1995; Lamade *et al.*, 1998a).

Following a period of inflorescence abortion, as many as five inflorescences may reach anthesis in a single month (Corley, 1977b). This indicates that inflorescences have accumulated at a stage before anthesis, and then opened in a flush. Chang *et al.* (1995) showed that the interval from leaf opening to anthesis of the subtended inflorescence was greatly prolonged in inflorescences both before, and more particularly after, a period of abortion. On individual palms, the range was from less than 250 days to over 350. This will contribute to seasonal yield variation if there is some synchrony of abortion among palms. Lamade *et al.* (1998a) also studied the interval from leaf opening to anthesis, and found similar variation, but following approximately an annual cycle, not apparently related to periods of abortion. They also found that male inflorescences took 10–15 days less than females to reach anthesis.

4.4.9 Conclusions

Many of the factors affecting yield components are now quite well understood, and the times at which the yield components are determined are known within broad limits. The timing of sex differentiation still remains uncertain, however. The timing changes with palm age, as might be expected from changing overall growth rates, and it apparently differs between clones. Interaction between external stresses and an internal cycle, dependent on feedback effects of fruiting activity, undoubtedly complicates responses, so that the same stress may cause different responses according to the state of the internal cycle (Jones, 1997).

4.5 YIELD

4.5.1 Yield of bunches

As we have shown in previous sections of this chapter, there are numerous management and environmental factors which influence yield. Management aspects are discussed in more detail in other chapters, but in all environments there is an underlying yield cycle. In mature palms, variation in bunch number contributes much more to these yield cycles than does bunch weight (Broekmans, 1957b; Brédas and Scuvie, 1960). Some examples of yield cycles from different environments are given in Fig. 4.17.

The yield cycle is of economic importance, because the volume of fruit in the peak month determines the size of mill, and hence the scale of investment, needed by a plantation. A standard assumption in Malaysia is

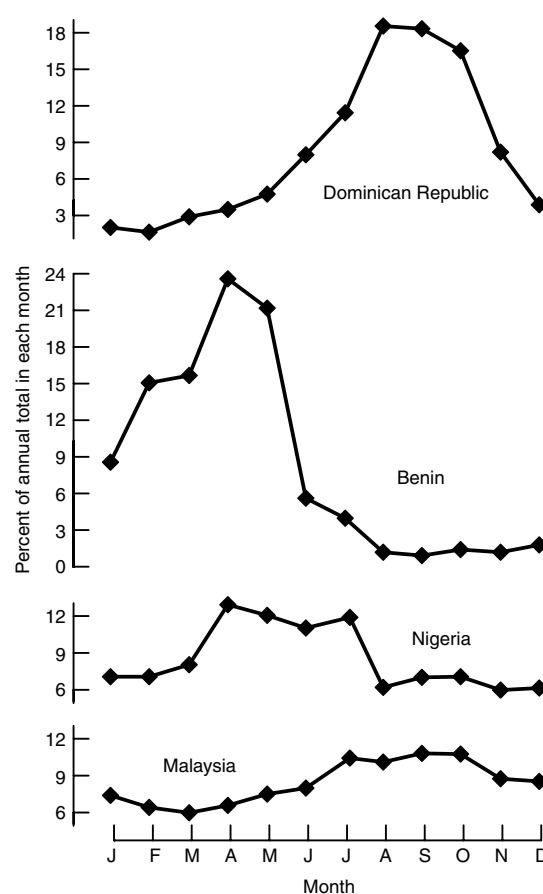


Fig. 4.17 Seasonal yield cycles in different environments.

that 12% of the annual yield will be harvested in the peak month (e.g. Fleming, 1969). In more extreme environments, either with a severe dry season or far from the equator, the peak month may reach 40% of annual production, with less than 1% in the lowest months (e.g. Nouy *et al.*, 1996). Surprisingly little attention has been paid to the possibility of reducing the fluctuations. In an extreme environment, this may not be feasible, but in Malaysia a period of disbudding, timed to remove the expected peak, shifted the peak forward by 6 months, with the loss of only about 5% of crop over the 2-year period of the trial (Corley and Teo, 1976). Manual disbudding of mature palms is not practicable on a commercial scale, so Ali Sekak *et al.* (1981) investigated the use of growth regulators for this purpose. They were able to reduce bunch number, but effects on the yield cycle do not appear to have been investigated.

Another way of reducing fluctuations is to plant a mixture of materials. Nouy *et al.* (1996) showed that, in the relatively uniform environment of North Sumatra, different families had quite different yield patterns, with peaks as much as 6 months apart in some years. In Benin, however, with a 5-month dry season, all families peaked at the same time.

4.5.2 Oil content of the bunch

Seasonal variation in oil to bunch or factory oil extraction ratio (OER) is regularly observed. (Oil/bunch normally refers to the results of laboratory analyses, discussed in Section 5.2.4; OER refers to factory-scale data.) An important cause of such variation in OER is variation in fruit set (Section 4.4.7.1). Since the introduction of the pollinating weevil to South-east Asia, seasonal variation in fruit set has diminished, but there still occur periods in which OER is low, apparently because fruit set is inadequate (Donough *et al.*, 1996a; Hoong and Donough, 1998). Effects of fruit set on OER can be distinguished from effects of ripeness, because poor fruit set also results in low kernel extraction ratio (KER), whereas underripe harvesting only affects OER, not KER. Donough *et al.* (1996a) showed that fruit set was correlated with the weevil population, which was in turn correlated with male inflorescence numbers (male inflorescences being the breeding sites for *E. kamerunicus*). Hoong and Donough (1998) found negative correlations between OER and rainfall 6 months earlier. This timing, and the fact that KER was also affected, suggested that fruit set was involved, and may indicate that the weevils are less active in wet weather. However, *E. kamerunicus* was specifically selected for introduction to Malaysia because its numbers were less reduced than those of other species during the wet season in Cameroon (Syed, 1982).

Apart from fruit set, other components of oil/bunch may also be affected by the weather. Dumortier (1999) noted a positive correlation between OER and sunshine hours in the previous month in PNG. Caliman and Southworth (1998) also found a positive correlation of OER with total radiation in the last 4 weeks before harvest, but it is not clear how radiation level affects OER. Hoong and Donough (1998) found negative correlations of OER with rainfall in the same and the previous month in Malaysia. This may be due to an effect of radiation on oil synthesis, with high rainfall corresponding to low radiation, but perhaps equally important is that bunches may have a higher water content in wet weather. Ochs and Daniel (1976) showed that oil/mesocarp tended to be depressed in bunches

harvested 2 months after the period of greatest moisture deficit in Benin. In Sumatra, Prabowo *et al.* (2002a) found appreciable differences in oil/bunch between different regions, with a higher value (30.9%) in the wettest climate, compared to 28% in two other regions. The difference was due to higher mesocarp weight and fruit weight per bunch; stalk, shell and kernel weights were much the same.

Environmental effects on OER have attracted attention in recent years because of a declining trend in OER in Malaysia (Ariffin and Jalani, 1994; Chew, 1996). It has been suggested that oil/bunch may decline with palm age, and a changing age profile for the Malaysian oil palm industry could explain the downward trend. However, most data on age effects come from comparisons, at a particular time, of plantings of different ages, so effects of breeding progress are confounded with age effects (e.g. Ho *et al.*, 1996). Data from a continuously recorded single plot of 11 palms in Malaysia were presented by Lim and Chan (1998) and showed no decline in oil/bunch over 25 years. Conversely, Sharma *et al.* (1999) compared the same three blocks before 12 years from planting, and after 16–25 years. In each case, oil/bunch was lower at the later date. These authors argued that the standard method of bunch analysis overestimates oil/bunch of very large bunches, and they used a modified method. Some doubt must remain about the decline with age, however, because they had not used the modified method at the earlier age.

Apart from possible effects of palm age or of climatic changes, OER is also strongly affected by management of harvesting (Gan *et al.*, 1995). The subject of bunch ripening is covered in Chapter 10. Genetic variation in oil to bunch ratio is discussed in detail in Chapter 5.

4.5.3 Effects of climate and weather on yield of bunches

There is little doubt that the major differences in yield between West Africa and Indonesia and Malaysia are attributable to the more favourable climates in the Far East. In particular, the length and severity of the dry season have a large effect on bunch number. Ochs and Daniel (1976) described an empirical relationship between soil water deficit and yield, which could be used to predict yield from rainfall data. This is discussed in Chapter 3.

Much of the work on the effects of weather on oil palm yield has involved a search for correlations between climatic factors and yield components, but many of these studies are flawed, because the existence of a correlation does not necessarily indicate cause and

effect. It is almost inevitable that correlations can be found between monthly means of two factors that both vary seasonally; depending on the choice of time lag, the correlation may be either positive or negative. If the expected direction of the effect is known, a correlation may help to identify the time lag; conversely, if the time lag is known, a correlation may indicate the direction of the effect, but without some prior information, a correlation may mean nothing.

In early work, prior knowledge was usually used to try to narrow the range of time lags to be studied, but with developments in computing power, recently there has been a tendency to put all possible variables and time lags into a multiple regression model (e.g. Robertson and Foong, 1977; Ong, 1982a, b; Chan *et al.*, 1985; Chow, 1992a). Not surprisingly, such studies have usually shown numerous correlations between yield and climatic variables, but as Ong (1982a) noted, many of these are probably spurious, and few of these studies have added to the understanding of how yields are determined. Some of the more useful results obtained are summarised in Table 4.7. It will be seen that correlations with time lags corresponding approximately to the expected times of abortion and sex differentiation have been found. The best study appears to be that of Dufour *et al.* (1988). They looked, not at monthly yield, but at deviations from the expected seasonal yield trend. By doing this, they automatically excluded correlations that result simply from the fact that bunch number and weather variables both have regular seasonal cycles.

Fruiting activity (Section 4.4.2) has also been shown to contribute to yield cycles. De Berchoux and Gascon (1965) showed a correlation between fruiting activity and abortion rate. Breure and Corley (1992) showed that fruiting activity affected sex differentiation, abortion rate and bunch weight. As already noted, this can lead to feedback oscillations, which will complicate attempts to understand effects of climate.

4.5.4 Yield forecasting

Most of the correlation studies mentioned above have been done with the aim of developing a method of yield forecasting. Forecasts of future yield are needed for planning labour and milling requirements, and would also be very useful to marketers, as forward selling of palm oil is common, and there is an active futures market (see Chapter 14).

The only method of forecasting that appears to be in widespread use is the 'Ulu Bernam' system; this was developed in Malaysia in the 1950s, but the only

published description is that by Loh and Sharma (1999b). This involves counting developing bunches on a sample of palms; based on the expected time interval of 5 months from anthesis to ripeness, this gives an estimate of bunch numbers to be harvested in the next 5 months. A 5% sample of palms is considered adequate, and bunch weights are based on previous age and seasonal trends (Ochs and Quencez, 1982). Refinements of this method involve subdividing the bunches into age classes, and adjusting expected bunch weights for the often-observed negative correlation with bunch number.

Another method of short-term forecasting is the 'auto-regressive integrated moving average' (Ahmad Alwi and Chan, 1990; Taib, 1985). This involves a statistical projection of past trends into the future, updated as each new month's yield data are added to the records. Ahmad Alwi and Chan showed that this method was at least as good as the Ulu Bernam method for a forecast 4 months ahead, and much cheaper (because it involves no counting of bunches in the field).

Longer term forecasting systems have mostly been based on correlations between yield and climatic factors, as discussed in Section 4.5.3. Some of these are listed in Table 4.8. There have been other studies, but the published descriptions of these have not always given sufficient information to allow the methods to be applied. The method described by Sparnaaij *et al.* (1963b) has apparently been used to forecast regional yields in eastern Nigeria, with good results (Purvis, 1973). However, the complexity of climatic effects on, and interactions among, components of oil palm growth and yield make it rather unlikely that regression methods, however elaborate, will be able to forecast yields very accurately. Thus, the future of yield forecasting may lie in computer simulation modelling.

4.5.5 Crop modelling

The underlying principle of crop modelling is reductionist: complex crop behaviour should be predictable from a relatively simple model. However, the enormous number of different processes and reactions involved in plant growth can very quickly lead to immensely complex models, which are essentially untestable, and unlikely to be valid beyond the environment in which they were developed. The greatest value of crop models is often not in practical prediction, but in forcing one to think logically about the variables and processes involved in the development of the crop. The attempt to construct a computer model always reveals gaps in knowledge, and can thus help in planning experiments to provide the information to fill such gaps.

Table 4.7 Correlations between climatic variables and bunch number or yield

Variables		Location	Time lag (months) ^a	Yield component probably affected	Effect	r^2 or R^2	Authors
Independent (climate)	Dependent (yield)						
Rainfall	Yield	Congo (1)	12	Abortion?	+ve	0.36	Hemptinne and Ferwerda (1961)
Rainfall	Yield	Congo (1)	31	?	–ve	0.64	Hemptinne and Ferwerda (1961)
Rainfall	Yield	Congo (2)	33	?	Quadratic	0.80	Hemptinne and Ferwerda (1961)
Water deficit	Yield deviations ^b	Ivory Coast	7–13	Bunch weight + abortion?	–ve	0.42	Dufour <i>et al.</i> (1988)
Water deficit			19–22	Sex ratio?	–ve		
Useful radiation (adjusted for water deficit)			24–25	Sex ratio	+ve		
Water deficit and radiation (as above)	Yield	Ivory Coast	12–25			0.72	Dufour <i>et al.</i> (1988)
Soil water, radiation	Yield	Malaysia	3–5	Fruit weight?		0.83	Foong (1982)
Radiation, temperature (+ fruiting activity)			9–11	Abortion			
Radiation, fruiting activity			15–20	Bunch weight?			
Temperature			18–20	Sex ratio?			
Soil water			18–23	Sex ratio?			
Soil water, radiation			27–29	Sex ratio?			
Radiation			36–38	?			
Soil water, temperature (+ fruiting activity)			39–44	?			

^aTime lags for correlations with bunch number or sex ratio at anthesis were adjusted by adding 5 months.

^bDeviations from mean seasonal trend.

Table 4.8 Yield forecasting systems based on correlations between climatic variables and yield

Variables		Location	Months ahead forecast ^a	r^2 or R^2	Authors
Independent (climate)	Dependent (yield)				
Useful rain (up to 30 mm/month)	Annual bunch number	Ivory Coast	21	0.91	Devuyst (1948)
Dry season rainfall	Annual sex ratio	Nigeria	24	0.49–0.69	Broekmans (1957b)
Rainfall	Annual yield	Congo	33?	0.80	Hemptinne and Ferwerda (1961)
Effective sunshine	Annual sex ratio	Nigeria	27	0.59	Sparnaaij <i>et al.</i> (1963b)
(sunshine hours adjusted for drought)					
Effective sunshine	Annual yield	Nigeria	28	0.71	Sparnaaij <i>et al.</i> (1963b)
(sunshine hours adjusted for drought)					
Active weeks (weeks without drought)	Annual sex ratio	Nigeria	29	0.62	Sparnaaij <i>et al.</i> (1963b)
Active weeks (weeks without drought)	Annual yield	Nigeria	30	0.90	Sparnaaij <i>et al.</i> (1963b)
Water deficit, radiation, temperature	Monthly yield	Malaysia	3	0.62	Robertson and Foong (1977)
Soil water, radiation, temperature, fruiting activity	Monthly yield	Malaysia	3	0.82	Foong (1982)
Water deficit, radiation	Monthly yield deviations	Ivory Coast	12	0.35	Dufour <i>et al.</i> (1988)
Water deficit, radiation	Monthly yield	Ivory Coast	12	0.68	Dufour <i>et al.</i> (1988)
Water deficit, radiation	Monthly yield deviations	Ivory Coast	6	0.42	Dufour <i>et al.</i> (1988)
Water deficit, radiation	Monthly yield	Ivory Coast	6	0.72	Dufour <i>et al.</i> (1988)

Time lags for correlations with bunch number or sex ratio at anthesis were adjusted by adding 5 months.

^aIn multiple regression models a range of time lags may be used; this column shows the shortest lag. For annual yield, some models use cumulative data over a period of months (e.g. Devuyst: rainfall from 21 to 33 months before harvest). The table shows the latest month required (e.g. for Devuyst, 21).

Several oil palm models have already been published; these range from simple models of single processes to very elaborate models covering all aspects of growth and assimilate partitioning. One of the simplest models is the overflow model, discussed earlier in this chapter: from figures for total dry matter production, this model predicts the partitioning between growth and yield. We have already seen that in some circumstances

this model is an oversimplification (Section 4.2.2), but like many models it works well in a certain range of situations.

The canopy assimilation model of van Kraalingen *et al.* (1989) has been used by several authors (Breure, 1988a; Henson and Chai, 1998) to estimate total dry matter production under optimal conditions. Partitioning of assimilates between vegetative growth and yield in

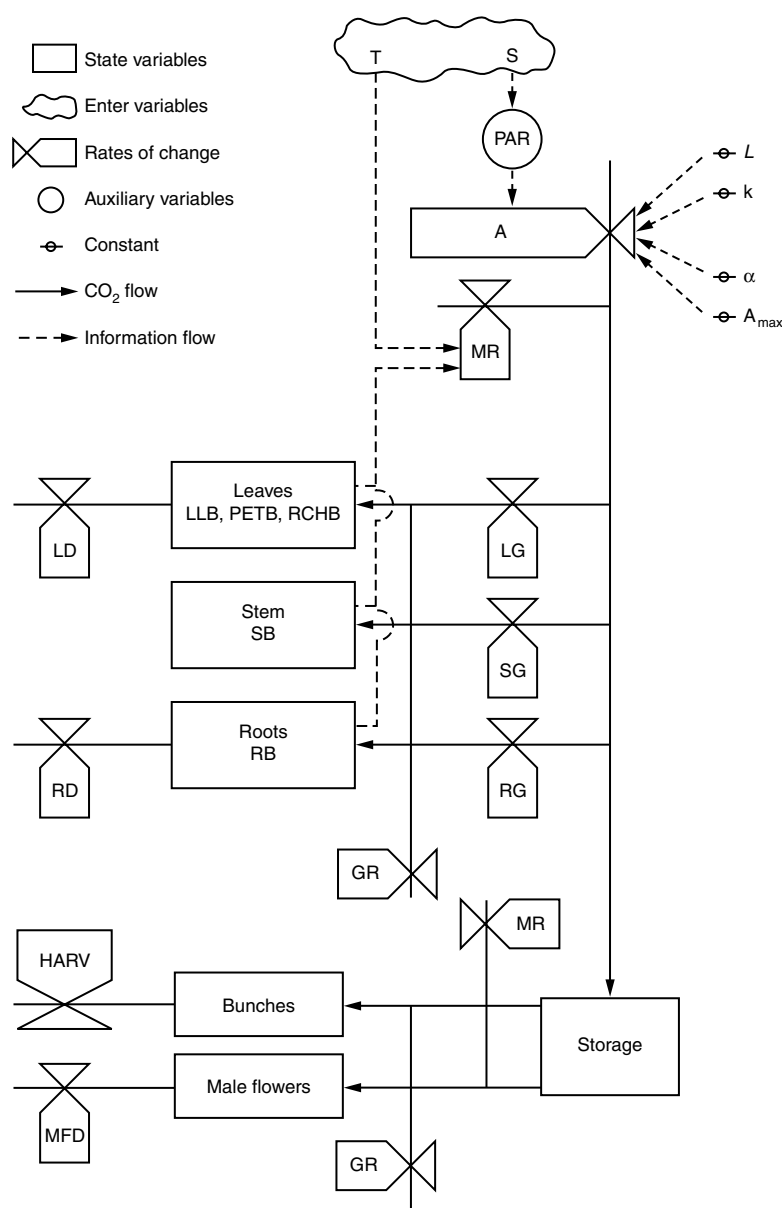


Fig. 4.18 Diagram of computer model of oil palm growth and yield. *L*: leaf area index; *k*: extinction coefficient; α : quantum yield of photosynthesis; *A*: photosynthetic rate; A_{max} : light saturated rate of photosynthesis; *T*: air temperature; *S*: total (global) radiation; *GR*: growth respiration; *MR*: maintenance respiration; *LG*: leaf growth; *SG*: trunk growth; *RG*: root growth; *LLB*: leaflet biomass; *PETB*: petiole biomass; *RCHB*: rachis biomass; *SB*: trunk biomass; *RB*: root biomass; *LD*: leaf death; *RD*: root death; *MFD*: male flower death; *HARV*: harvest. (From Dufrene *et al.*, 1990.)

this model was based on the overflow model, while partitioning among vegetative components was fixed, based on data from the literature. As noted in Sections 4.1.4.3 and 4.3.1.2, simulation of maintenance respiration presented particular problems, and there is clearly room for improvement in this model. In the model of Dufrene *et al.* (1990) (Fig. 4.18), growth rates of different vegetative parts can be varied independently, but yield still consists of what is left after vegetative requirements are satisfied.

The canopy photosynthesis model of van Kraalingen *et al.* (1989) is complex, involving calculations of light distribution through a three-dimensional model of the canopy and the light response curve for photosynthesis (as in Fig. 4.2). Henson (1998b) produced a much simpler model, which could be used to estimate total canopy photosynthesis from hourly data on solar radiation and VPD, but included site-specific constants based on preliminary measurements.

Canopy photosynthesis has attracted most attention from modellers, but Jourdan and Rey (1997a, b)

described a model to simulate the spatial growth of the oil palm root system. This produced very elegant pictures of palms and plantations 'seen' from below (see Section 11.2.1.2), but it was not clear whether the model would help with understanding palm growth or yield.

The models listed above attempt to simulate annual growth and yield, rather than within-year seasonal yield fluctuations, but for the forecaster, the latter is of greatest interest. Jones (1997) described a model incorporating external stress effects and internal feedback loops to predict bunch numbers. He showed that a wide variety of different flowering patterns could be produced, by varying the length (time lag) of the feedback loops and the critical stress thresholds. He suggested various ways in which his model could be tested and improved, but no attempts appear to have been made to develop a yield forecasting system based on such a model.

Chapter 5

Selection and Breeding

The aim of oil palm breeding is to maximise oil and kernel yield, and thus contribute to plantation profitability. The breeder will select parent palms for high yield of fruit, and for high oil and kernel content, and make crosses between the best individuals. Subsidiary objectives may include reduced height, for ease of harvesting, and tolerance to diseases and stresses. In order to make progress, the breeder must start with a population of palms in which there is genetic variation for yield. The origins of the main breeding populations, and the history of oil palm breeding starting from the early twentieth century, are reviewed in Section 5.1. A noticeable feature is the small number of ancestral palms in some of the populations; this means that variation is limited, and has led breeders to look for new material in wild palm groves, to increase genetic diversity (Section 5.1.7). Starting with a variable population, the breeder must then decide which characteristics to select for: selection criteria and methods of measurement are discussed in Section 5.2. It is easier to make improvements from one generation to the next (selection progress) for characters that are highly variable, and for which much of the variation is due to genetic differences, not to environmental factors; variation in yield and its components are described in Section 5.3, and genetic analysis is discussed in Section 5.2.6.

In the early days, oil palm breeders simply made crosses between the highest yielding individual palms. In Indonesia and Malaysia, with the Deli *dura* (Section 5.1.1), good progress was made, but in Africa, thin-shelled *tenera* palms were chosen for their high oil/bunch, and when these were crossed, 25% of the offspring were sterile *pisiferas*. This was unfortunate, but led quickly to understanding of the inheritance of shell thickness and to the emergence of the *dura* $\times$ *pisifera* (D $\times$ P) cross (Section 5.1.5).

The need to keep *dura* and *pisifera* populations separate has encouraged the adoption of complex breeding schemes (Section 5.4). There appear to have been two main influences on oil palm breeding: maize breeding and animal breeding. The oil palm is monoecious, and

is naturally cross-pollinated; the most important monoecious crop is maize. A breeding system known as reciprocal recurrent selection (RRS) has been extensively used in maize, and many oil palm breeding programmes are essentially based on this approach. In Section 5.4.2, RRS is compared with family and individual selection (FIS), which is probably the most common approach used in animal breeding (in this chapter, 'family' and 'progeny' are both used to refer to a group of palms with the same parents). Detailed results of some programmes are presented, and the increase in yield that has resulted from breeding is evaluated, in Section 5.5.

Current commercial seed production programmes are briefly reviewed in Section 5.1.7. In the 1990s, over 140 million oil palm seeds were produced per year around the world (Rajanaidu and Jalani, 1999b), sufficient to plant over 600,000 ha. The introduction of vegetative propagation of the palm by tissue culture is an important development, reviewed in detail in Chapter 6. Planting of clones should eventually lead to further yield increases, but commercial plantings up to the time of writing were very limited, and clonal propagation has had no effect on world palm oil production as yet. As commercial planting of clones increases in importance, though, it is likely that breeding methods will change; this aspect is discussed in Section 5.4.5.

5.1 HISTORY OF SELECTION

The establishment of plantations on a large scale commenced in the 1920s, both in the Congo and in the Far East, and work on the improvement of the crop by selection and breeding quickly followed. In the Congo, selection was in the hands of the Institut National pour l'Étude Agronomique du Congo Belge (INEAC), while in the Far East the work was undertaken by the large plantation companies of Indonesia and Malaysia and by the Algemene Vereniging van Rubberplanters ter Oostkust van Sumatra (AVROS) and the Department of Agriculture, Malaya.

With great differences in the material available in the two regions, the approach to improvement was also different. In Africa the poor quality of *dura* fruit, and the natural occurrence of *tenera* palms, led to an early concentration on the production of high-quality *tenera* material. In the Far East, the relatively high quality of the *duras* from the Deli ornamental avenues, and the limited alternatives, tended to confine the early work to the provision of seed from selected Deli *dura* palms for further planting. In 1922 AVROS stated that the Deli type should remain the standard oil palm for Sumatra until breeding had done its work with the offspring of newly imported breeding materials.

Rosenquist (1986) introduced the term 'breeding population of restricted origin' (BPRO) to describe populations that can be traced back to distinct, usually small, groups of wild or unimproved ancestral palms. In the following sections, we have attempted to trace the origins and development of the more important BPROs currently in use by oil palm breeders. These pedigrees are useful in planning a breeding programme, to avoid inbreeding (Section 5.4.3). It must be noted, however, that until the inheritance of shell thickness was understood, there was no way of telling

whether a cross had been made correctly, and some of the published pedigrees may be incorrect, because of illegitimate out-crossing.

5.1.1 Indonesia and Malaysia

5.1.1.1 *Deli dura* in Sumatra

Little information exists regarding the yield and quality of the original unselected plantation populations of Deli palms; the few publications from Indonesia were concerned largely with crosses between Deli and imported material. Schmöle (1930) accepted Blommendaal's figures of 62–63% mesocarp, 30% shell and 7–8% kernel to fruit as being 'average components' in 1929. He also suggested 100 kg of fruit per palm as an average annual yield of the first generation on good soil.

The origin of the four Bogor palms has been discussed in Chapter 1, and the probable ancestry of some of the present-day Deli *dura* breeding populations is summarised in Fig. 5.1. In most cases these populations have undergone several generations of selection after their derivation as shown in Fig. 5.1; the further development of some populations is discussed in

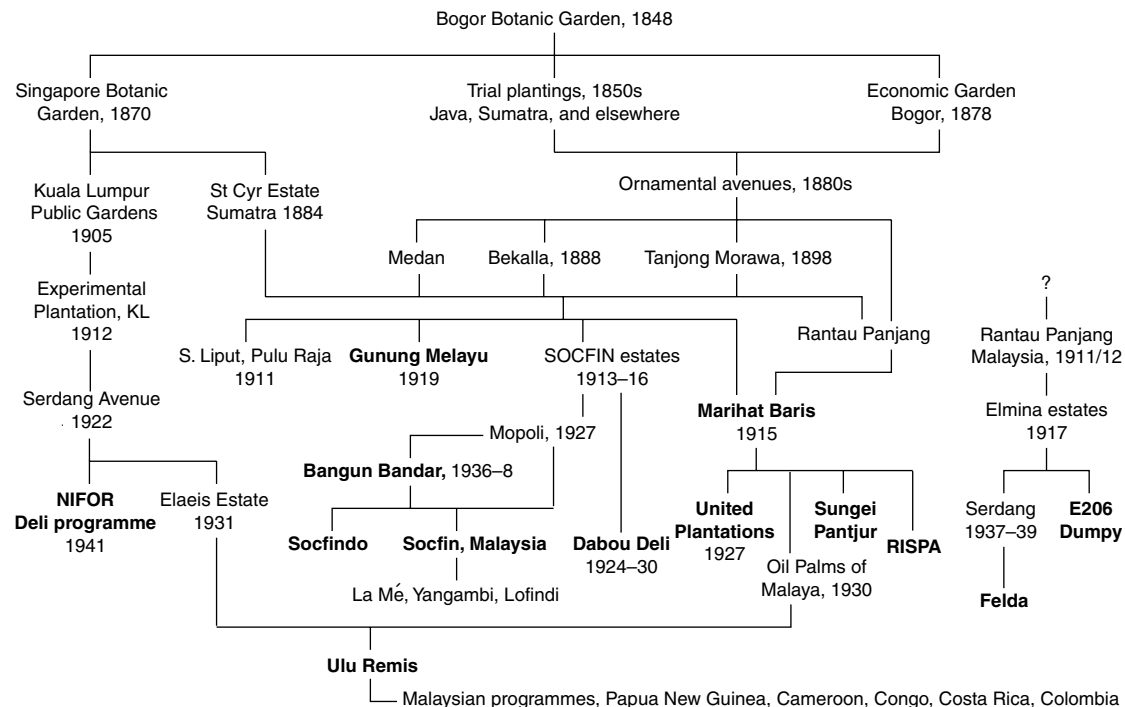


Fig. 5.1 Possible ancestries of Deli *dura* breeding populations. Some important present-day populations are presented in bold type.

Section 5.1.6. Figure 5.1 is based mainly on Hardon and Thomas (1968), Rosenquist (1986), Hartley (1988) and Pamin (1998), but it is not comprehensive, and there remain some uncertainties. Some points not brought out in previous reviews are listed below.

- Trial plantings were established in the 1850s all over Indonesia (Sumatra, Java, Sulawesi, Maluku, Lombok and Kalimantan; Pamin, 1998). These pre-date the Bogor Economic Garden planting of 1878, and may be the source of some of the later estate plantings (e.g. Mopoli; Carrière de Belgaric, 1951; not shown in Fig. 5.1).
- Oil palms were planted in the Singapore Botanic Gardens in 1870 (Burkill, 1966), again pre-dating the Economic Garden planting, and probably with seed from the original Bogor palms. E.A. Rosenquist (pers. comm., 1995) suggested that the Serdang Avenue palms are probably descended from this source, not from the Bogor Economic Garden as shown by Hardon and Thomas (1968). The Serdang Avenue seed is recorded as coming from the Kuala Lumpur Public Gardens planting of 1905 (Jagoe, 1952b), and Rosenquist believed it likely that the officer in charge of the gardens would have approached his opposite number in Singapore for seed, as both were under the gardens department of the same colonial administration.
- Stoffels (1934) stated that the best mother palms used for the original Pulu Radja estate and Tamiang plantings were those in the St Cyr and Tandjong Morawa avenues, but that, owing to an insufficiency of planting material, seed had also to be taken from poorer specimens in the gardens of Medan. The manager of St Cyr is quoted as stating that his seed came from Singapore (Maas, 1923), presumably from the Botanic Garden.

An important point to note from Fig. 5.1 is that if one compares, say, pure Serdang Avenue material, as in the Nigerian Institute for Oil Palm Research (NIFOR) Deli programme, with Dabou Deli, these two populations had probably already been separate for at least four generations at the time when they were first planted. The Deli *dura* is generally considered as a single BPRO, but subsequent separation in different breeding programmes, stressing different selection objectives over several generations, and perhaps with unconscious inbreeding, may have led to some differentiation between populations. Whether or not to treat such populations as separate BPROs is arbitrary, but Okwuagwu (1993) observed that, when different Deli populations were crossed, the variation between palms for fresh fruit bunch (FFB) yield, bunch number and bunch weight was as great as when unrelated *duras* were crossed (see also Section 5.5.1.4).

There are no published fruit or bunch analysis figures from the original Bogor palms, none of which now survive. Hartley (1988, p. 191) stated 'Illegitimate progeny of [the Bogor palms] planted in West Africa in 1958, indeed showed a remarkable similarity in appearance ... but the fruit analyses were not similar to modern Deli, being more akin to some of the *dura* found in African groves'. No data were presented, but this comment implies that the original Deli may have had mesocarp/fruit of no more than 50%, with the higher figures in later generations being the result of selection. However, Lee *et al.* (1990) found about 60% mesocarp/fruit in a population assumed to be unselected descendants of the original Bogor palms, and Table 5.1 shows that this was typical for early Deli material, together with about 30% shell/fruit and 8–10% kernel/fruit. The progeny of later generations of Deli planted in West Africa have always shown typical Deli composition (Hartley, 1988).

Table 5.1 Fruit composition of early Deli *dura* material

Source of data	F/B	M/F	O/M	S/F	K/F	O/B	Ref.
F0 selections	66.1	67.2	48.8	–	–	21.6	1
F1 progenies	66.2	66.6	50.4	–	–	22.2	1
Average Deli (Schmöle)	–	62.5	–	30.0	7.5	–	1
Aek Pantjur	58.8	56.8	–	–	–	–	2
Serdang Avenue mean	64.9	61.0	–	–	7.4	–	3
Bogor Economic Garden	60.4	59.7	47.9	30.4	9.9	17.3	4
Tanjong Morawa Avenue	62.4	61.0	48.8	29.3	9.7	18.5	4
Elmina Estate	60.9	58.5	48.4	32.2	9.2	17.2	4

F: fruit; B: bunch; M: mesocarp; O: oil; S: shell; K: kernel.

References: 1: Hartley (1988); 2: Pronk (1953); 3: Jack and Jagoe (1932); 4: Lee *et al.* (1990).

One of the first attempts to select within Deli material through the evaluation of proper records was made at Marihat Baris estate in North Sumatra, where 2000 palms, planted in 1915, were recorded from the time they came into bearing. In 1922 self-pollination of 15 palms was carried out in co-operation with AVROS and progenies were planted in the selection areas at Sungei Pantjur and Polonia between 1924 and 1931. The factors sought were high bunch yield, high bunch number, mesocarp thickness of 4 mm or more, and absence of crown disease (Section 12.1.5.1). The selected palms were selfed and crossed, for both seed production and the next generation at the selection stations. The selections were made at a very early age and the progeny were characterised by early bearing, suggesting that precocity was a factor unconsciously selected for and inherited.

Another plantation group, SOCFIN (Société Financière de Caoutchouc, later Socfindo), followed initial Deli selection with two generations of selfing or with one generation of selfing followed by a generation of crosses, at Mopoli and Bangun Bandar, North Sumatra. Few details are available for this selection and breeding work, but from the F1 selfs yields 50–60% above those of the initial population, and a further 12–40% increase in the next generation, were claimed (Carrière de Belgarric, 1951; see also Potier *et al.*, 2000). These figures are impressive, but part of the yield increase was undoubtedly attributable to improved planting methods or the use of more fertile areas. Attempts to distinguish breeding progress from agronomic improvements are discussed in Section 5.5.2. The yields and bunch analysis of the selected F1 palms at the two centres appeared strikingly similar. Bunch yield of the selections was about 200 kg/palm per annum, fruit/bunch ratios were 60–61% and mesocarp/fruit ratios 68–69%.

A further population of interest is that known as Gunung Melayu. A Swiss company started planting this estate in 1919, and made selections for low height increment and high oil/mesocarp. Molecular marker studies have suggested that the Socfindo and Gunung Melayu populations are closely related (C. James and P.L. Jack, pers. comm., 1996). It is possible that the Gunung Melayu selections were from the same source as the Bangun Bandar plantings in 1936. Plantings made in the 1930s were still yielding 18 t FFB/ha per year 42 years later (Rosenquist, 1986). The current breeding material is derived from plantings made in 1942, and selections made in this planting in the mid-1980s had an average of 50.4% oil/mesocarp (Anon., 1990) which, as Table 5.1 shows, was high for early Deli *dura* material. However, height increment for Gunung

Melayu $\times$ AVROS crosses was not less than for other Deli $\times$ AVROS crosses (Lee and Pang, 2000).

5.1.1.2 *Deli dura* in Malaysia

The first recorded introduction of oil palm to Malaysia was from the Gold Coast (Ghana) to the island of Labuan in the 1870s, but all of the palms were apparently destroyed in 1889 (*Kew Bulletin*, 1877).

Kushairi and Rajanaidu (2000) reviewed the origins of most Malaysian breeding programmes. The early estates in Malaysia obtained open-pollinated seed from the ornamental avenues and other plantings in Sumatra, and the Deli *dura* became the established plantation palm (Plate 5.1). There are several distinct Deli BPROs in Malaysia: the Serdang Avenue palms, the Ulu Remis population (which incorporates some Serdang Avenue material), the Johor Labis (Socfin) material and palms from Elmina estate, including the Deli Dumpy. The Ulu Remis population is represented in almost every Malaysian programme, and in several outside Malaysia.

As mentioned above, and shown in Fig. 5.1, the Serdang Avenue material (Plate 5.2) may have come from Bogor via Singapore. Oil Palms of Malaya imported seed from Sumatra to plant Ulu Remis estate in Johore in about 1930, and the Ulu Remis breeding population was chosen from several thousand palms yield recorded from 1934 onwards (Rosenquist, 1986). This material probably came from Marihat Baris, although as Fig. 5.1 shows, material had reached that estate by more than one route. Rosenquist (1999) noted that this material still existed as distinct lines in later generations of the Ulu Remis programme, whereas there was no 'pure' Serdang Avenue material. The only pure Serdang material still in existence may be that at NIFOR.

There is some confusion over the origin of the Elmina estate material in Malaysia. Rosenquist (1999) mentions that the seed came from Rantau Panjang, Sumatra, but Hardon and Thomas (1968) and Pamin (1998) state that it came from Rantau Panjang, Malaysia. The latter seems more likely, as Hartley (1988) mentions that the material for Tenamarram estate (planted before Elmina) came from a nursery at Rantau Panjang; it is unlikely that nursery seedlings would be shipped from Sumatra. It does not appear to be recorded where the Rantau Panjang seed came from.

Jack and Jagoe (1932) studied a block of 589 10-year-old palms at Elmina estate and found considerable variation in yield and fruit composition. A number of selections was made, and selfs and a few crosses were planted at Serdang in 1937–1939; this material is still



Plate 5.1 A typical avenue of oil palms from which so much of the industry of the Far East is developed. This avenue was in Perak, Malaysia. (T. Menendez.)



Plate 5.2 The Serdang avenue palms in 1962. (T. Menendez.)

represented in the Felda breeding programme (Chin and Shuhaimi, 1999). Jagoe (1952a) described how two of the palms under observation at Elmina were seen to have an unusually large girth and slow height increase; one of these palms was the well-known Dumpy E206. Selfed and crossed progeny of E206 were planted at Serdang just before World War II; this was fortunate as the original mother palms on Elmina estate were all felled during the Japanese occupation of Malaya. The selfed progeny of Dumpy E206 was quite uniform, with the large girth and small annual height increment being inherited (Table 5.2; Plate 5.3). Hartley (1988) commented that crosses of Dumpy with other palms were intermediate in girth and height, but Rosenquist (1990) pointed out that each cross is closer in height to

Table 5.2 Height and girth of Dumpy palm E206 and its progeny

	Girth at 122 cm (cm)	Height to base of crown (cm)	Age (years)
Original E206	287	335	15
'Normal' palms at Elmina	226	518	15
F1 Selfed E206	272	292	12
Cross E206 × E268	249	406	12
Selfed E268	249	475	13
Cross E206 × E152	221	411	12
Selfed E152	206	417	13



Plate 5.3 E206 Dumpy F₁ self at Serdang. Twenty-six years old. Note the characteristic 'blunt' leaf tip of this progeny.

the tall parent selfing than to the Dumpy self. However, comparison of selfs and crosses tells us little about inheritance of 'dumpiness', because selfing is known to depress height (Section 5.4.3). Fruit characters of E206 were poor, but some of the E206 × tall crosses were much better, so a programme of 'back-crosses' between these and their half-sibs, the E206-selfed progeny, was started. True back-crosses could not be made owing to the destruction of the parent palm. The so-called back-crosses, together with F₂ Dumpy selfs, were distributed to a number of estates in Malaysia and considerable populations of these palms were established. An interesting feature of the Dumpy is its very strong resistance to *Fusarium* wilt (Rosenquist *et al.*, 1990).

Another important programme in Malaysia was that of SOCFIN. This company imported material from

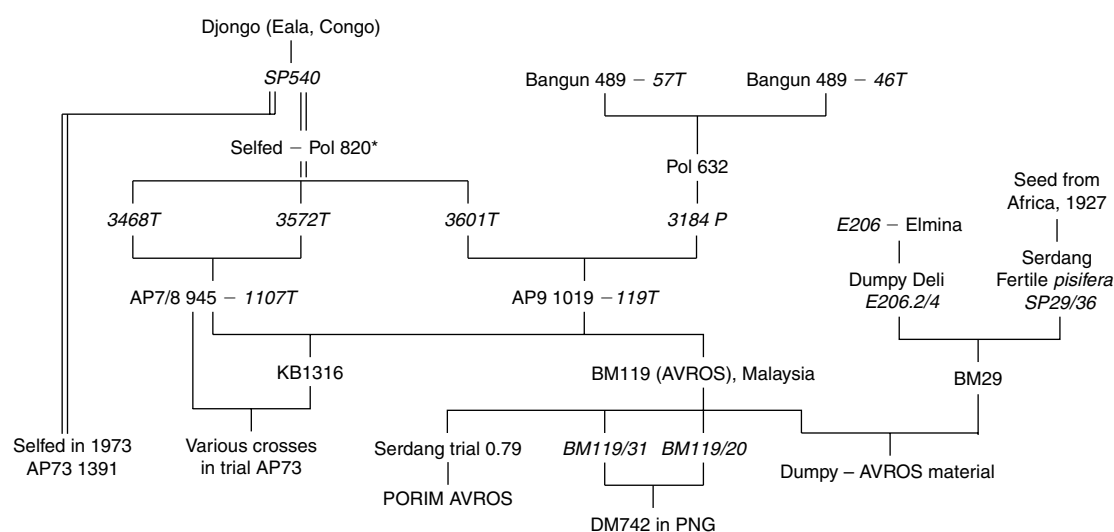
Sumatra in the 1930s, probably from the programme of its sister company Socfindo. The breeding programme commenced after 1945, and material was distributed in the 1950s to the Ivory Coast and Yangambi (Congo). The SOCFIN programme was closed in 1983, but samples of material were planted by the Palm Oil Research Institute of Malaysia (PORIM) (Kushairi and Rajanaidu, 2000). Material of SOCFIN origin was also returned to Felda in Malaysia from the Ivory Coast in the 1970s.

5.1.1.3 *Tenera and pisifera in Sumatra*

In spite of the good quality of the Deli material there was interest in importing material from Africa from the early days of breeding in Sumatra. There are records of imports to Bogor in 1914–1915 and to several estate

Table 5.3 Some early imports of African material to Indonesia and Malaysia

Location	Date	Origin of material	Important descendants
Tanah Itam Ulu	1914	Yangambi	Dolak Sinumbah: H5, EX5
Kwalah Krapoh	1920	Congo	Bangun Bandar
Sungei Pantjur	1921	Eala Botanic Garden, Congo	SP540, AVROS <i>pisiferas</i>
Mayang	1931	Cameroon	Marihat
Chemara Research	1947	Pisifera pollen from Yangambi and Nigeria	PA series <i>pisiferas</i>



*Pol 820 was at least partly illegitimate (see text).

Fig. 5.2 Ancestry of AVROS and some related material. Palm numbers are shown in italics; other numbers are progeny codes.

groups and AVROS a few years later. Some of the early imports are listed in Table 5.3. Much of the African *dura* material, being inferior to Deli, was eliminated at an early stage, both from government selection stations and from the estates of plantation companies, but as mixed plantations existed in the early days it seems likely that some subsequent plantations were 'contaminated' with non-Deli characters through outcrossing.

Serious breeding work with imported material was started by AVROS soon after World War I; trials of Deli crosses with Deli $\times$ import *dura* and *tenera* and with crosses within African material were planted at Sungei Pantjur and Polonia (Pronk, 1955). In retrospect, by far the most important single palm was the *tenera* SP540 at Sungei Pantjur, which was part of a consignment of seed sent by the Director of the Eala Botanic Gardens in Congo. The seed was recorded as 'var. Djongo', indicating that it came from the Djongo *tenera* palm, which made an important contribution to the Yangambi programme from 1922 onwards (Section 5.1.2). A total

of only 13 seedlings survived; eight were *duras* and five *teneras*, so the Djongo seed was presumably an open-pollinated *tenera* $\times$ *dura* (T $\times$ D) cross. SP540 is one of the ancestors of the AVROS *pisiferas* now widely used for seed production in Indonesia, Malaysia, Papua New Guinea (PNG) and Costa Rica (Section 5.1.7). It is of interest to note here that seed from Eala was imported into Colombia some 15 years later and provided one parent of unquestionably 'Yangambi-type' *tenera* to be found at Calima. Thus, it is almost certain that a great quantity of good *tenera* in all three continents is descended from the Djongo palm.

Figure 5.2 shows the ancestry of the AVROS material, and some other descendants of SP540. Rosenquist (1990) pointed out that, while the descent of the Deli *dura* population from only four palms is often emphasised, the fact that AVROS *pisiferas* are apparently descended from only two palms is rarely mentioned. This pedigree is misleading, however, the selfing of SP540 apparently had only two *pisiferas* among 123 palms (Hartley, 1977,

p. 201), whereas about 30 would be expected from a *tenera* selfing (Section 5.3.3.1). Thus, Pol 820 must have been, at least in part, an illegitimate $T \times D$ out-cross, but at that time the inheritance of shell thickness was not understood, so this was apparently not recognised. AVROS material is sometimes referred to as being '75% Djongo', but if SP540 was from open-pollinated seed and Pol 820 was illegitimate, there might be no more than 12.5% of genes from the Djongo palm in present-day AVROS material. There were only eight *duras* from the Djongo seed batch, so there is a possibility that the illegitimate pollen came from nearby Deli *duras* and that Pol 820 was actually half Deli. However, molecular markers indicate that AVROS and Deli are quite distinct (see Section 5.2.8.2 and Fig. 5.8), so the illegitimate *dura* parent of Pol 820 was probably not a Deli *dura*.

Apart from the widely distributed AVROS lines, there are other descendants of SP540 in some programmes. The Bangun Bandar fertile *pisifera*, 3184, was crossed not only with palm 3601 but also with 3520 from Pol 820; material descended from that cross is in the Marihat programme (Lubis, 1990; Hutomo and Pamin, 1995). A repeat selfing of SP540 was made in 1973; Rosenquist (1986) noted that this selfing was very low yielding, but Hutomo and Pamin (1995) compared *pisiferas* from this cross with AVROS *pisiferas*, and found little difference in yield of their progenies. Palm SP540 was blown down by wind in 1995 (Pamin, 1995).

Even with the early illegitimacy, present-day AVROS material is highly inbred. This makes selection within pure AVROS families difficult (see Section 5.4.3), but does not have detrimental effects when AVROS is out-crossed to unrelated *duras* for seed production.

The Bangun Bandar cross 489, from which one ancestor of AVROS lines was derived (see Fig. 5.2), was apparently imported from Africa in 1914 or 1915 (Asmono *et al.*, 1999), but its origin is not known. Numerous more recent imports to Indonesia are listed by Lubis (1990).

5.1.1.4 *Tenera and pisifera in Malaysia*

In terms of present-day programmes, the most significant import to Malaysia was the AVROS cross, planted as BM119 in 1957 (see Fig. 5.2); Rao *et al.* (1999) list the recent history of this material in Malaysia. Other importations included bulked *pisifera* pollen imported by Oil Palms of Malaya from Congo in 1947; this was crossed onto Deli *duras* to produce *teneras*, which were then intercrossed, or crossed with further *tenera* imports, mostly from Nigeria. The resulting crosses were planted at four times normal density, and the *duras*

and *teneras* were removed once fruiting started. The *pisiferas* remaining formed the PA series of Guthrie Research Chemara (Yong *et al.*, 1999).

Pisifera SP29/36 (see Fig. 5.2, and also Section 5.5.1.5) was derived from an importation by the Department of Agriculture, but there seem to be no records of where this came from. From the 1960s onwards, there were numerous exchanges with other countries, and a great diversity of material was imported, so that most BPROs are now represented in Malaysia.

5.1.2 Congo

The history of selection and breeding in the Congo is the history of the emergence of the $D \times P$ cross. The early work in the Congo was quite different from that of the Far East, and it was the realisation of the value of the *tenera* by Ringoet, and the meticulous and inspired work of Beirnaert, that made it possible for the *tenera* era to develop within 30 years of the establishment of the first plantations. Beirnaert (1933a–c) described the early Congo selection work in both its practical and theoretical aspects in considerable detail.

Ten open-pollinated *tenera* bunches were used for the establishment of the Palmeraie de la Rive at Yangambi in 1922. One was from the famous Djongo (meaning 'the best') palm at Eala, which had 55% mesocarp and 30% oil to bunch, and the other nine were from groves at Yawenda. The planting was at close spacing, and *dura* and poor types of *tenera* were gradually eliminated. Further fields were planted in 1924 and 1927 with open-pollinated *tenera* seed from a plantation at Ngazi, where 16,000 palms had been under observation. Fields planted in 1929 and 1930 were from seed of *teneras* collected in the Palmeraie de la Rive after the elimination of *duras*.

After thinning out, the remaining palms in these fields were yield recorded and the highest yielders were evaluated by bunch analysis. These data were examined in stages, with the elimination of many palms at each stage. Finally, after 3 years of observation when the palms were mature, minimum standards were laid down for the choice of mother palms (*arbres-mères*). These standards were not applied rigidly, and exceptional performance in one respect allowed a palm to be selected even though it was below standard in another. The standards laid down are of interest. The mesocarp/fruit percentage was low, at 75%, reflecting the initial difficulties in finding high-quality *tenera*; later breeding raised this figure considerably. Bunch production, at 140 kg/palm per year, was very high for conditions in Congo and among the original selections it was not often achieved. Large fruit and a kernel of at least 1 g in weight were

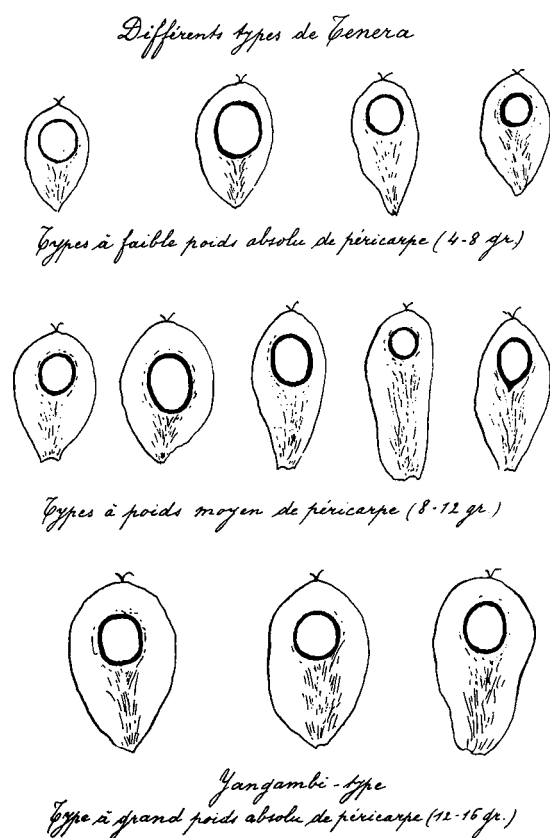


Fig. 5.3 Beirnaert's drawings of different types of Congo tenera (Beirnaert, 1933c).

thought to be advantageous. It was admitted that larger fruit size may sometimes be indicative of poor fruit set, but it was claimed that larger fruit would have advantages in milling. Hartley (1988, p. 204) pointed out that there does not appear, on either theoretical or experimental grounds, to be any virtue in large fruit *per se*, although there have been suggestions that large fruits lead to higher oil/bunch (Section 5.3.3.2).

All these considerations led to the selection of a distinctive type of fruit, the Yangambi type, which was large and ovoid, with a large, thin-shelled nut placed a little above centre and a wide basal portion of mesocarp (Fig. 5.3). These characters of the early Yangambi-type tenera fruit have made them relatively easy to identify, and descendants of the first selections can be found in many parts of the world. Very small numbers of this type of fruit existed in the original material. Of the selected palms in the Palmeraie de la Rive over 70% were descended from the Djongo palm at Eala.

The high mesocarp oil content of the tenera fruit encouraged the distribution of $T \times T$ seed for commercial planting in the Congo in the 1930s. As explained in Section 5.3.3.1, 25% of *pisiferas*, which are usually female sterile, segregate from such crosses. This had not been a problem earlier, as open-pollinated seed, from teneras usually surrounded by duras, would have been predominantly $T \times D$. Once the problem was understood, the way was open for the development of the $D \times P$ cross (Sections 5.1.5 and 5.1.6).

Selection and breeding came to an end at Yangambi in 1959, but several of the best lines had been established at Binga, a plantation that included a former substation of Yangambi; Rosenquist (1986) regarded this material as a distinct BPRO. The ancestry of the Binga population is shown in Fig. 5.4, and further development of this programme is discussed in Section 5.1.6.1. Yangambi material has also reached the Ivory Coast, Nigeria, Cameroon, Malaysia, Indonesia and Colombia, as discussed by Rosenquist (1986).

In parallel with the INEAC programme, the Unilever plantation company Huileries du Congo Belge (later Plantations Lever au Zaïre, now Plantations et Huileries du Congo) had a breeding programme, including material selected from Pindi and Brabanta estates in southern Congo. Other origins included in the Binga programme were Mayumbé (short palms, from INEAC prospections west of Kinshasa) and Mongana (from the district around Lisala, and characterised by high oil/bunch).

5.1.3 West Africa

There were three main programmes in West Africa, in the Ivory Coast, in Nigeria and in Cameroon.

5.1.3.1 Ivory Coast and Benin

The La Mé population resulted from a survey made by M. Houard between 1924 and 1930 in the Bingerville region of the Ivory Coast (Cochard *et al.*, 2000). Nineteen palms were chosen (or 29 palms, according to Gascon and de Berchoux, 1964), mostly from the Bingerville botanic garden, but some from concessions and wild groves in the district. These palms were selfed, and the progeny planted at La Mé. According to Cochard *et al.* (2000), only five of the original palms are still represented in the La Mé breeding population.

The Pobé population is descended from 38 tenera palms selected in 1927 from wild groves in the Porto-Novo and Pobé regions of Benin (Gascon and de Berchoux, 1964). Some of the palms were exceptionally short

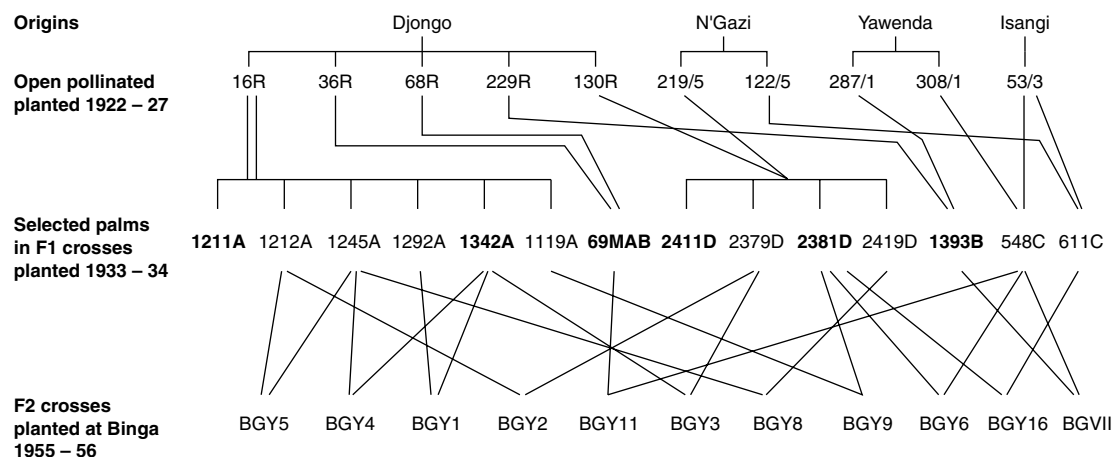


Fig. 5.4 Ancestry of Yangambi material at Binga. Six F1 palms selected for INEAC diallel are shown in bold type (see Section 5.1.7.1). Djongo palms are all believed to be half-sibs; other origins may not be derived each from a single palm. (Hardon *et al.*, 1976; Rosenquist, 1986.)

stemmed, but fruit composition of these was poor, with very thick shells for *tenera* palms.

After its establishment in 1945, the Institut pour Recherche sur les Huiles et Oléagineux (IRHO; succeeded by CIRAD-CP, Centre de Coopération internationale en Recherche Agronomique pour le Développement–Culture Pérennes) organised the *Expérience Internationale*, involving exchanges of material between the IRHO stations in the Ivory Coast, Benin and Congo Brazzaville, with INEAC, and with SOCFIN in Malaysia. Material was introduced from Yangambi in 1949–1952 and also from Sibiti, in Congo Brazzaville, at about the same time. The Yangambi crosses are listed by Houssou *et al.* (1989); they are descended from the same ancestral open-pollinated palms as are shown in Fig. 5.4, but from different F1 selections. According to Cochard *et al.* (2000), the Sibiti population was descended from open-pollinated seed from the Palmeraie de la Rive at Yangambi (Section 5.1.2).

The Robert Michaux plantation at Dabou was planted in the 1920s, with Deli *dura* material from Socfindo in Sumatra, probably from Mopoli (Cochard *et al.*, 2000). IRHO acquired control of the plantation in 1946 and selected 250 palms as seed parents. Other Deli origins have been added to this Dabou Deli population subsequently. In recent decades, the IRHO initiated and participated in numerous exchange programmes with other centres, and there are now 21 different populations represented at La Mé (Cochard *et al.*, 2000).

5.1.3.2 Nigeria

In Nigeria, the early work was concentrated on a population of some 800 palms of different forms and types planted at Calabar in 1912–1916. *Dura*, *tenera*, *virescens* and mantled fruits were used to provide seed and, except for the *tenera* planting, only one parent of each form or type was used (Smith, 1929). The much higher bunch yield of the *dura* palms led to the assumption that *duras* would in general yield more than *teneras*; however, this result appears to have been quite fortuitous and due to the qualities of the single original grove *dura*. A series of selfs and crosses of these palms was planted on four stations in Nigeria in 1930 and sterile *pisifera* palms soon appeared in the T × T material. The yield superiority of the *dura* was carried into this generation and led to biased seed distribution in favour of *dura* for some years. Although there was later shown to be little justification for this bias, it did mean that large-scale release of T × T seed, which in the Congo had resulted in 25% sterile *pisiferas* in commercial plantings, was avoided.

Another pre-World War II selection was carried out among palms of grove origin at Aba. Controlled pollination was not fully successful and populations of several thousand largely out-pollinated palms were established at the Oil Palm Research Station near Benin in 1939–1941. The progeny, derived from four Aba *tenera* parents, formed a useful source of further breeding material and, with the large numbers of *teneras* produced, gave no support to the theory that the latter were

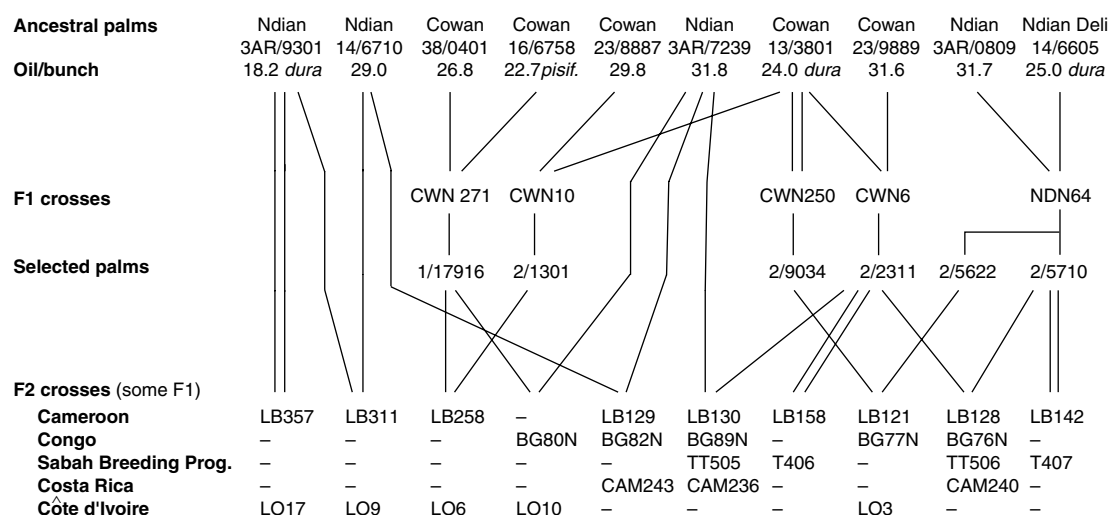


Fig. 5.5 Ancestry of some widely distributed crosses from the Ekona population. From Rosenquist (1986) and Rao *et al.* (1999); ancestral oil/bunch data from A.G. Prendergast (pers. comm., 2001) and Green (1973); palms were *tenera* unless shown otherwise. Numerous other crosses were planted in Cameroon and Congo, and some in Malaysia; Rao *et al.* (1999) give further information for Malaysia.

inherently lower yielding than *dura* palms. The *dura* material proved to be of little interest. Some material was also introduced from Angola: six palms were planted at Njala in Sierra Leone, and crosses between these were planted in Nigeria in 1942 (Sparnaaij *et al.*, 1963a). In the 1960s, material from the NIFOR programme was distributed to Ghana (van der Vossen, 1969b) and to Cameroon (Rosenquist *et al.*, 1990).

Large quantities of seed issued within West Africa by NIFOR owe their origin to the Aba and Calabar programmes and to later generations from them. Mention should be made of the outstanding Calabar *dura*, CA256 (or 551.256), which produced good selfed progeny and was used in many crosses; its fruit composition was exceptional for African *dura*, with 31.2% shell and 10.3% kernel to fruit. The frequency of *virescens* specimens in Nigerian seed is largely due to the inheritance of this character from two Calabar *duras*, 551.341 and 551.375, of good composition, and from some *virescens tenera* crosses and selfs.

5.1.3.3 Cameroon

The origin of the Ekona population is described by Rosenquist (1986) and Rao *et al.* (1999). Experimental plots were planted in the botanic gardens at Victoria in 1903 (Farquhar, 1913) and included thin-shelled palms, apparently from a village called Lisombe. As noted in

Chapter 2, the term *lisombe* subsequently became synonymous with *tenera*. The first plantations in Cameroon were established before 1913; Ikassa estate was planted around this time, probably with seed from the Ekona district, perhaps with some selection. The United Africa Company planted N'dian estate from 1928 onwards, using seed from Ikassa, and also from the Calabar plots (Section 5.1.3.2), together with a small amount of seed from Congo, and Deli *dura* from Malaysia.

Selection at N'dian started before 1933, and both controlled and open-pollinated seed from 800 selected palms was used for further plantings at N'dian, and also at Cowan and Calabar estates in Nigeria. In 1949, Prendergast undertook a large programme of selection for both yield and resistance to *Fusarium* wilt on Cowan and N'dian estates, using yield records from 35,000 palms, and bunch analysis, including oil/mesocarp determinations, on the higher yielders. In 1951, a programme was planned using 19 *teneras*, six *duras* and two fertile *pisiferas* (Green, 1973); these palms were notable for their high oil/bunch (see Fig. 5.5, but note the difficulty in comparing oil/bunch data between different stations; Section 5.2.4). Crosses and selfs were planted at Lobe estate in Cameroon in 1954–1957. It was envisaged that some of the selfings would later be back-crossed to their parents (A.G. Prendergast, pers. comm., 2001); this was not followed up, but a few second-generation selfings and sib-crosses were made.

Various crosses were sent from Cowan to Malaysia, Brazil, Surinam, Peru and Costa Rica in the 1950s. Crosses of later generations were distributed to Malaysia (Rao *et al.*, 1999), Costa Rica (Sterling and Alvarado, 1995), the Congo and the Ivory Coast; the ancestry of some of this material is shown in Fig. 5.5.

5.1.4 Latin America

There were several historical centres for oil palm breeding in Latin America. Material was introduced both from Africa and from the Far East, and some work was also done with *Elaeis oleifera* and interspecific hybrids.

5.1.4.1 Central America

The United Fruit Company (later United Brands, now ASD de Costa Rica S.A.) established a research centre at Lancetilla, in Honduras, in 1926, to evaluate new crops. Oil palm seeds were imported between 1927 and 1929 from Sierra Leone, Nigeria, the Congo and the Far East, including Bogor and Serdang, Malaysia (Richardson, 1995). When it was seen that the Java and Sumatra material was more productive than that from Africa or Malaysia, most of the latter material was cut down, though not before some Malaysian illegitimate progenies had been established at San Alejo (Hartley, 1988). Open-pollinated seed from the Bogor Deli material, in particular, was distributed in the 1930s and 1940s in Honduras, and to Costa Rica, Cuba, Peru, Colombia, Ecuador, Guatemala and Panama. The African material was little used, and only nine palms are represented in the present ASD breeding programme, which commenced in Costa Rica in the 1960s.

A large collection of *E. oleifera* material was started by United Fruit Company in the 1960s. In the course of this work, a natural *E. oleifera* × *E. guineensis* hybrid was found in Costa Rica. Palms with a short trunk and short leaves, known as 'compact', have been developed by repeated back-crossing of this palm to *E. guineensis* (Sterling *et al.*, 1988).

5.1.4.2 Colombia

Seed was brought from the Congo to Colombia by Florentin Claes in 1931, and open-pollinated seed of the Djongo palm was imported by M.J. Rivero in 1936 and planted at Palmira, near Cali. From these introductions V.M. Patiño made *tenera* selections, and a second generation which included some legitimate progenies was established at Calima in 1947 (Patiño, 1948, 1958).

The *tenera* are of the Yangambi type and the whole population was used, together with Deli *dura* from Honduras, in a selection and breeding programme at the El Mira station of the Instituto Colombiano Agropecuario (ICA) at Tumaco.

5.1.4.3 Venezuela

The La Esperanza plantation has an interesting collection of planting material from Yangambi, Sumatra and West Africa, including exceptionally fertile and productive *pisifera* palms (Hartley, 1988).

5.1.4.4 Brazil

Seed were sent from Nigeria to Brazil in the 1950s (from Cowan estate; see Section 5.1.3.3), from the Ivory Coast in the 1960s (Dabou and Socfin Deli *dura*, La Mé, Yangambi, Sibiti; see Section 5.1.3.1), and Deli *dura* and AVROS material from Malaysia in the 1970s (Nascimento *et al.*, 1982).

5.1.5 The emergence of the *dura* × *pisifera* cross

The superior oil content of the *tenera* led to the distribution of T × T seed for commercial planting in the Congo in the 1930s. By 1938 it was known that as much as 25% sterile palms could be expected in these *tenera*-derived commercial plantings. The hybrid nature of the *tenera* was recognised by Beirnaert when he examined the fruit form of the progeny of his selfed and crossed mother palms. A count of 29,454 palms in 15 blocks at Yangambi showed that 24.3% were *pisifera*, not significantly different from the 25% that would be expected from segregation of a single gene (although a few crosses had percentages of *pisifera* differing significantly from 25%, as discussed in Section 5.3.3.1).

Examination of the progeny of D × T crosses showed no *pisifera*, and for the majority of these crosses the segregation was close to 50:50 *dura*:*tenera*. It was also noted that *tenera* seed taken from grove palms, surrounded almost entirely by *dura* palms, gave progeny in the proportion 357 *tenera* (50.5%):336 *dura* (47.5%):14 *pisifera* (2%), the last being accounted for by assuming that a small quantity of *tenera* pollen might naturally fertilise female *tenera* inflorescences.

A full explanation of the presence of steriles was published by Beirnaert (1940). In this paper Beirnaert showed clearly the inheritance of the shell-thickness character, and brought forward evidence against the theory, current in French West Africa at that time, that the

tenera was a 'degenerating form' of the oil palm. He also stated the steps to be taken to prevent further sterility in new plantings, namely that $D \times T$ and $T \times D$ seed should replace $T \times T$ seed for a short period, after which full *tenera* production should be assured by the issue of $D \times P$ seed. The full information obtained from the Yangambi F1 plantings was published in 1941, after Beirnaert's death (Beirnaert and Vanderweyen, 1941).

Confirmation of the 'Congo theory', as it was at first called, was not long in coming from other territories, although publication was tardy. The Calabar *tenera* selfs and crosses in Nigeria in due course showed their general agreement (Hartley, 1957), and $D \times P$ crosses including Delis as parents were seen to provide *tenera* progeny (Vanderweyen, 1953; Toovey and Purvis, 1956). In Sumatra many $D \times T$ and several $D \times P$ crosses had been made before World War II and instances of 50% *dura* and 50% *tenera* in the progeny of the former were already known. The first large-scale confirmation of *tenera* production from $D \times P$ crosses came when Pichel (1956) reported that several hundred hectares of $D \times P$ crosses in the Congo were 98% *tenera*. One of the first large-scale plantings of $D \times P$ material in the Far East was in 1953 on Pabatu Estate in Sumatra (Janssen, 1959). Developments in Malaysia were not far behind, and in 1956, Pamol Estate took delivery of the first 99,000 $D \times P$ seeds produced by Chemara, using Deli *dura* females and *pisifera* pollen imported from Unilever estates in Nigeria and the Congo (Rosenquist, 1990; A.G. Prendergast, pers. comm., 2001).

Today, all commercially produced seed and all estate-scale plantings are $D \times P$. However, many smallholders still plant palms grown from unselected seed picked up in existing plantings; in the Ivory Coast, Cheyns *et al.* (2001) found that 40% of smallholders had planted unselected material. Such seed are $T \times T$, and will segregate to give 25% sterile *pisiferas* and 25% *duras*; yield potential will be at least 30% below that of $D \times P$ material.

5.1.6 Current breeding and seed production programmes

Several breeding programmes have already been mentioned in a historical context, and some of these still continue today, but as the oil palm industry has expanded, so has the number of breeding programmes increased. In 1995, a total of over 140 million $D \times P$ seeds were produced, at some 30 production centres around the world (Rajanaidu and Jalani, 1999b). In many of these centres the emphasis is not really on breeding, but on the selection of parents within well-known base

populations, for production of commercial planting material. In Malaysia, for example, the great majority of the seed produced is Deli $\times$ AVROS, and some producers have little other material in their programmes apart from these two populations. Brief descriptions of the main programmes, and the origins of the seed produced, are given in the following sections, but the list is not exhaustive.

The almost exclusive use of the Deli as the mother palm was questioned by van der Vossen (1974). He showed that, where no inbreeding had occurred, the actual bunch yields and yields predicted from genotypic values were closely similar, but with the partially inbred Deli population actual yields were below those predicted. In the NIFOR material he examined, high yield in the out-crosses did not depend on a Deli palm being one of the parents. Calculations of breeding values for Deli and African *duras* in one programme in Malaysia have also shown little to choose between the best palms (V. Rao and R.H.V. Corley, unpubl.). Rosenquist (1986) showed that there was less variation in the Deli than is available in African material, and Ooi (1975b) found that crossing Deli *duras* with unrelated Congo material appreciably increased additive genetic variation for bunch number and mean bunch weight. Hartley (1988, p. 281) suggested that the idea that the Deli population should be either kept pure, or used exclusively as the female parent in seed production, might unnecessarily prolong dependence on a limited and inbred population, but with few exceptions the Deli *dura* continues to be used as the female parent for seed production throughout the oil palm world.

5.1.6.1 Africa

Following the lead of INEAC in the Congo (see below), several oil palm breeders in Africa have adopted forms of RRS (Section 5.4.2.1). This requires two base populations; the source material has been predominantly *tenera* on the one side and Deli *dura* on the other, but the methods of choice have varied. In several programmes, one base population has been composed of palms yielding a small number of large bunches (usually Deli), the other being palms with a large number of smaller bunches.

Congo: After the recognition of the inheritance of shell thickness, INEAC planned a programme, the first phase of which consisted of a diallel cross between six *teneras* (Pichel, 1956). The planned programme was essentially RRS, the intention being that high-yielding *tenera* $\times$ *tenera* combinations could be reproduced in commercial quantities by combining *duras* in the selfed

progeny of the one *tenera* with *pisiferas* in the selfed progeny of the other. The *teneras* to be used, as listed by Hardon *et al.* (1976) are shown in Fig. 5.4. Owing to political unrest in the Congo in the 1960s, this programme was not fully implemented; of the 36 possible combinations, 20 were planted by 1960.

Much of the material was also planted at Binga, and the 'Joint Research Scheme', based at Binga and started in the 1970s, combined this with material from the Unilever programme at Yaligimba and with imports from most of the main centres in other countries (Dumortier *et al.*, 1992). Out of this developed a 'Combined Breeding Programme' in the 1980s, described by Rosenquist *et al.* (1990), and involving exchanges between the Congo and Cameroon, Indonesia, Thailand, PNG and Colombia. Seed produced at Yaligimba in the 1990s included Deli and African *duras* (the latter particularly for wilt-resistant material), crossed with a wide range of *pisifera* origins. Parents were selected by FIS (Section 5.4.2.2), avoiding inbreeding but otherwise without regard to origin.

Ivory Coast: The origin of this programme, set up by IRHO, later CIRAD-CP, has already been described. Gascon and de Berchoux (1964) used the Deli as almost their sole *dura* source, although a few palms of Angolan origin were included (Meunier and Jacquemard, 1990), which had large mean bunch weight, comparable to Deli *dura*. The other side of the programme consisted largely of *teneras*, but included some *pisiferas*. These varied considerably in quality and were obtained from four separate origins: La Mé, Pobé (Benin), Yangambi/Sibiti and NIFOR. Following prospection work in the Ivory Coast, Yocoboué material was also included (Section 5.1.7.1).

The early work showed that crosses between Deli and African origins yielded significantly more than crosses within origins (Gascon and de Berchoux, 1964). This 'interorigin' effect is now recognised as resulting from heterosis or hybrid vigour in crosses between unrelated material (Durand-Gasselin *et al.*, 2000a). The first cycle of test crosses in the RRS programme was planted in the Ivory Coast and Cameroon, and compared over 500 crosses, of which 15 were selected (Gascon *et al.*, 1981). Trials with some 1300 test crosses from the second RRS cycle were planted, in partnership between CIRAD-CP and Centre National de Recherche Agronomiques in the Ivory Coast, with Institut National de Recherche Agronomique du Benin, with Institut de Recherches Agronomiques pour le Développement in Cameroon, and with Socfindo and the Indonesian Oil Palm Research Institute in Indonesia (Cochard *et al.*, 1995). A third cycle is being planned in Africa (Baudouin *et al.*, 1997). Progress achieved in this programme is discussed in Section 5.5.2.3. Commercial seed is produced

as 'reproductions' of the selected crosses from the test programme, using *duras* and *pisiferas* from selfings of the parent palms (Section 5.4.2.1).

Nigeria: The breeding programme at NIFOR was, as in the Ivory Coast, essentially based on RRS. *Dura* seed palms came from *dura* selfs and crosses as in the IRHO programme, but also from the *tenera* selfs, as in the INEAC programme. The *dura* source was not confined to Deli palms, but it was thought best to determine separately the value of the best Delis available and to compare them with good African *duras*, so these sources of *duras* were kept separate. An appraisal of the NIFOR programme was undertaken by West *et al.* (1977) and more recently by Okwuagwu (1989). Many high-quality *tenera* palms with below 7% shell have emerged; material from Nigeria bred in the Ivory Coast has given *tenera* progenies containing palms with 83–90% mesocarp and only 4–9% shell (Hartley, 1988, p. 269).

Ghana: Material from NIFOR was introduced to Ghana, and van der Vossen (1974) used data from the NIFOR programme to compute genetic values for parents of the Ghanaian programme. A list of material in the programme was given by Wonkyi-Appiah (1998), and the programme was described by Wonkyi-Appiah (1999). Some mutation breeding was done, but without useful results.

Cameroon: There were two main programmes in Cameroon: the IRHO programme at La Dibamba, which included much the same material as in the Ivory Coast programme (see above), and the Pamol programme at Lobe estate. D × P seed production in the Pamol programme commenced in 1953 at Cowan and N'dian estates (Section 5.1.3.3). Production was based on Ekona material, with no Deli *duras*, and using fertile *pisiferas*. Seed production was later moved to Lobe estate, with the addition of imports from NIFOR in the 1960s, and the emphasis on fertile *pisiferas* was dropped. The method adopted was essentially a form of RRS. Rosenquist *et al.* (1990) gave some information on this programme, material from which has been distributed, through exchanges, to Congo, Malaysia, Colombia and Costa Rica.

5.1.6.2 The Far East

Indonesia: The course of oil palm breeding in the Far East was severely checked by World War II. Breeding by AVROS was continued under the new name of the Research Institute of the Sumatran Planters' Association (RISPA). Marihat Research Station was also set up, and the current programme of the Indonesian Oil Palm Research Institute (IOPRI) incorporates both the Marihat and the RISPA programmes. The material,

listed in detail by Lubis (1990), includes at least seven distinct subpopulations of Deli *dura*, together with African *teneras* including AVROS, Yangambi, La Mé and NIFOR. The general strategy adopted is RRS (Lubis *et al.*, 1990).

Other programmes in Indonesia are those of Socfindo, London Sumatra Indonesia (Anon., 1990), and a consortium of Tania Selatan and Asian Agri Group (Breure, 1998). The last of these involves testing 450 D × P crosses at three sites in Sumatra, with the parents of the crosses, from the ASD programme in Costa Rica (Section 5.1.7.3), available as 225 *dura* selfings (all Deli) and 60 *pisifera* clones (Yangambi, AVROS, Calabar, La Mé and Ekona).

Malaysia: Until the early 1970s, Malaysian breeding organisations participated in numerous exchanges with centres in Africa, and representative samples of most populations were established. The *Experience Internationale* has already been mentioned (Section 5.1.3.1). Another early exchange programme was the Sabah Breeding Programme, organised by the Department of Agriculture in Sabah in the 1960s and based on RRS. *Tenera* material from Cameroon and Nigeria was imported, in exchange for Deli *duras* from several sources. Rajanaidu *et al.* (1986a) published some results of this programme, based on 5–6 years' yields and limited bunch analysis at two centres, and concluded that the programme contained valuable breeding material. Nearly all of the trials showed significant yield and fruit character differences between progenies, and interactions between sites and progenies were not significant. Some good progenies emerged in the D × T crosses, NIFOR palm 32.005 (Calabar) in particular showing good yield and oil to bunch when crossed with Malaysian Deli. *Tenera* selfs all showed inbreeding depression in yield, but some T × T crosses of mixed origin gave both *dura* and *tenera* of high yield and good fruit analysis.

The establishment of a breeding and genetics centre, the Oil Palm Genetics Laboratory (OPGL), by four of the principal Malaysian plantation companies in 1965, was intended to give a firmer genetic basis for selection and breeding, and to assist and interpret the selection and seed production programmes of the contributing companies. The aims were to study existing breeding populations, introduce new material, establish progeny trials, evaluate experimental designs and study all factors related to yield. The method adopted was a system of family and individual mass selection, with *pisifera* selection based, in the first instance, on the performance of *dura* and *tenera* sibs in T × T crosses, and when available on the results of D × P progeny tests. Progeny testing entails recording a second generation (Section

5.4.2.3), and the results are then compared with those of the second round of selection in the T × T crosses (Hardon *et al.*, 1973). In a second stage of this programme, started in the early 1970s, it was possible to take account of the results of the D × P progeny tests and to make use of the *pisifera* palms available from the early T × T crossings. The first round of D × P tests had shown highly significant progeny differences but very little genotype × environment interaction (Chan *et al.*, 1986).

In the early 1970s, the Malaysian government banned the export of commercial seed, with the aim of discouraging the expansion of plantings in competing countries. Exchanges of breeding material, as distinct from commercial seed, were not banned, but also came virtually to a stop. Over the next two decades, Malaysia built up a very comprehensive collection of material from wild palm groves all over Africa and Latin America (see Section 5.1.7). The export ban was partially lifted in 1996 (Venugopal, 1999).

With the steady expansion of the Malaysian oil palm industry, more and more organisations have started breeding and seed production. According to Kushairi and Rajanaidu (2000), who outlined the origins of material in the major programmes, there were 13 commercial seed producers in 1997. Nine of these produced Deli × AVROS material, and all used Deli *duras* exclusively as female parents. The Felda programme also produced Deli × Yangambi material (Chin and Shuhaimi, 1999), as did Guthrie (Yong *et al.*, 1999), IOI and United Plantations. *Pisiferas* of Dumpy × AVROS ancestry were used by some seed producers (see Fig. 5.2). Origins of the material in the major programmes are outlined in Rajanaidu and Jalani (1999a).

Thailand: Two breeding programmes were established in Thailand in the 1990s, as described by Palat *et al.* (1999) and Anupunt *et al.* (1998). Both programmes include a diversity of origins.

Papua New Guinea: The Dami Oil Palm Research Station programme in West New Britain started in the late 1960s, with rather narrow samples of Deli and AVROS material from Malaysia (Dumortier and Konimor, 1999). The programme, loosely based on RRS, produces Deli × AVROS seed of good performance, but the need to broaden the genetic base has been recognised (Dumortier, 2000), and Dami participated in the Combined Breeding Programme exchanges in the 1980s (see Congo, above).

5.1.6.3 Latin America

The majority of the early plantations in Latin America owe their origin to the seed introduced in 1926 to

the Experimental Garden at Lancetilla in Honduras (Section 5.1.4.1). The spate of planting that started around 1960 was composed either of Honduras material obtained direct or second hand, and crossed with *pisifera* locally established or imported as pollen, or of imports from the Ivory Coast, Cameroon, Malaysia and Surinam.

Costa Rica: As noted in Section 5.1.4.1, United Fruit Company started a collection of *E. oleifera* material in the 1960s, and the widespread interest of oil palm breeders in this species allowed the material to be exchanged for advanced breeding lines from several other research centres. As a result of these exchanges, the present ASD de Costa Rica programme contains a wide variety of different BPROs (Richardson, 1995). The seed produced is predominantly Deli $\times$ AVROS, but Deli $\times$ Ekona and Deli $\times$ Calabar (ex-NIFOR, via Ghana) crosses are also produced (Sterling and Alvarado, 1995; Escobar *et al.*, 1999). Performance of the latter materials in comparison to AVROS is discussed further in Section 5.5.1.2.

Colombia: Deli *dura* seed production was started in Colombia in 1958 by Instituto de Fomento Algodonero, using material from Lancetilla (Section 5.1.4.1). The programme was taken over by Instituto Colombiano Agropecuario in 1969, and from 1973 *pisiferas* from Calima (Section 5.1.4.2) were used to produce D $\times$ P seed (Bastidas *et al.*, 1993). Another Colombian seed producer is Murgas y Lowe, at Hacienda Las Flores, producing Deli $\times$ AVROS seed derived from the Dami programme (see *Papua New Guinea*, above). An extensive collection of material from the Combined Breeding Programme (see *Congo*, above) has been established elsewhere in Colombia, but is not yet being used for seed production.

Ecuador: In Ecuador a breeding programme was started with imported material and seed is being produced. Nigerian *pisifera* pollen was first used, but locally bred *pisifera* have now been selected (Hartley, 1988).

Brazil: Brief descriptions of the breeding programmes of CEPLAC (Comissao Executiva do Plano da Lavoura Cacaueira) and EMBRAPA (Empresa Brasileira de Pesquisa Agropecuaria) were given by Barcelos and Amblard (1999). CEPLAC produced seed for smallholders, using Deli *dura* parents from Malaysia. The EMBRAPA programme was based predominantly on IRHO material (Dabou Deli and La Mé). Material has also been collected from the semi-wild groves in Bahia (see Section 1.1).

5.1.7 Prospection and conservation

It will be apparent from the above descriptions that, despite the vast wild or semi-wild populations existing

in the palm belt across west and central Africa, most breeding programmes have a narrow genetic base and can be traced back to only a few palms. The need for new material of sufficient genetic variability to provide scope for future breeding progress has been widely acknowledged for a long time, and the earliest important prospection was that carried out in Congo in the 1920s. Prospection work did not receive strong emphasis in most centres, though, because it was thought that more immediately promising results would be obtained by the use, in crosses, of the restricted lines already available; in the Far East the industry was satisfied with Deli *dura* material for more than a third of a century.

5.1.7.1 Prospection by African centres

Post-World War II prospection in Congo was done on estates planted with Yangambi material, among palms of local origin on estates, and in grove areas. Candidate seed parents, which were largely *tenera* on estates and *dura* in the groves, were selected after fruit and bunch analysis and yield recording (Vanderweyen, 1952b). In the area of northern Congo only one *tenera* palm would be selected out of up to 35,000 palms examined (Pichel, 1956). The rigour of this selection may be gauged from the fact that while 'average' Yangambi *tenera* had mesocarp/fruit and oil/bunch contents of 70 and 22%, respectively, selected mother palms at two centres had contents of 92.5% mesocarp/fruit and over 32% oil/bunch. In southern Congo (Kwango) about 420 ha was searched, but only 17 provisional selections were made. Of these, the *teneras* selected showed a fruit and bunch analysis very similar to those obtained in the north (Desneux, 1957).

The first prospectations in Nigeria covered only very small areas. Apart from the Calabar plots, an old grove area at Aba covering 11 ha and another grove area of 49 ha at Ufuma were included. The Ufuma grove was chosen because of the very high proportion of *tenera* palms (43%). The grove underwent various thinning processes, but finally about 2% of the original stand was selected. Fruit analysis was not impressive; shell/fruit varied from 11 to 19% and mesocarp was never over 79% (estimated by the boiling and pounding method, equivalent to 85% by modern analysis methods). The selected palms were pollinated with mixed pollen from the best of their number, and the resulting progenies gave a mean mesocarp/fruit 6% above that of the parents (Hartley, 1988, p. 251).

In the early 1960s a prospection in grove areas in eastern Nigeria was undertaken, and 72 open-pollinated progenies were established at the NIFOR Main Station.

Mean *tenera* values for mesocarp/fruit ranged from 72 to 84% in eight of the areas chosen, and shell/fruit from 6.7 to 11% (Hartley, 1988, p. 252). Fruit size varied greatly and fruit well up to the size of Deli fruit were frequently encountered, some very similar to Deli fruit, and there was a great variation in spine length in the spikelets.

In the Ivory Coast, a systematic prospection was carried out by Meunier (1969). The groves there are in general less dense and more scattered than those in Nigeria. About 100 palms were taken at random in each of 11 areas. The proportion of *tenera* varied from 0 to 41%, and only seven *pisifera* were found. *Virescens* palms were rare, only one *albescens* was found and no mantled palms were encountered (see Section 5.3.3.3 for further discussion of fruit types). Areas with the highest proportion of *tenera* tended to have the best mean fruit composition. Where *dura* of good composition were found, the *tenera* were also of good composition. There were wide differences between groves in bunch and fruit weight as well as composition, and populations could be grouped according to their fruit and bunch characteristics. Some data from this prospection are given in Table 5.5, but these are not directly comparable with the Nigerian data in the table, as in the latter prospection the palms were not taken at random.

Populations from the coastal region of Yocoboué and Sassandra were chosen as being superior to the existing La Mé material (Section 5.1.3.1) and close to the imported Congo material (Yangambi-Sibiti), for mesocarp to fruit and bunch weight (Meunier, 1969). Selfs and crosses between 14 palms were introduced to the IRHO breeding programme (Cochard *et al.*, 2000), but it appears that only two or three of these were eventually used (Bakoumé *et al.*, 2000).

The IRHO undertook further prospectings in Cameroon in the 1970s. Populations in seven different areas were observed, and open-pollinated seed from three palms and pollen from five others were collected from Widikum (Cochard *et al.*, 2000). Blaak also collected wild material in Cameroon, in the 1960s, from the Bamenda Highlands (Rosenquist, 1986; see Section 5.3.6.2).

A major prospection exercise was undertaken in Nigeria in the 1970s, jointly between NIFOR and the Malaysian Agricultural Research and Development Institute (MARDI, whose oil palm work was later taken over by PORIM, now known as the Malaysian Palm Oil Board, MPOB). Ataga and Fatokun (1989a) described some of this material, which is discussed in more detail in the next section. Further prospection was done by NIFOR in 1991 in marginal areas on the northern edge of the oil palm belt in Nigeria (Ataga *et al.*, 1999).

Table 5.4 Estimates of variance components for vegetative characters and yield components in PORIM Nigerian collection

Character	% of total variation attributable to		
	Populations	Families within populations	Palms within families
Rachis length	9.9	6.7	79.4
Leaf area	3.4	2.2	94.1
Mean bunch weight	6.9	1.5	91.6
Mesocarp/fruit	24.1	9.3	66.6
Oil/dry mesocarp	2.0	4.8	91.2

From Lawrence and Rajanaidu (1986). Analyses are based on six palms per family, with five families from each of 40 collection sites (populations).

5.1.7.2 Prospection by the Malaysian Palm Oil Board

N. Rajanaidu, of MPOB (formerly PORIM), has undertaken a series of prospection exercises throughout the oil palm belt in Africa. The first collection was made in the early 1970s, jointly with NIFOR in Nigeria (see above). Open-pollinated bunches were taken from over 900 palms (595 *duras* and 324 *teneras*) from 45 sites. This collection was planted in Malaysia, and also at NIFOR. Very detailed evaluation was done in Malaysia (Rajanaidu and Rao, 1986, 1987, 1988; Rajanaidu *et al.*, 1983, 1989, 2000b).

Lawrence and Rajanaidu (1986) used fruit and vegetative measurement data from 200 families, five from each of 40 sites (regarded as populations), from the PORIM Nigerian collection to determine the best sampling strategy for collecting and conserving a wild oil palm population. The families consisted of seedlings from the same open-pollinated bunch, and were thus probably half-sibs (with the same mother, but different pollen parents). They drew three main conclusions from the results of their analyses (Table 5.4).

- First, they showed that, although for leaf area and oil/dry mesocarp almost all the variation was between individuals within families, there was significant variation between populations for some characters. Nearly a quarter of the variation in mesocarp/fruit arose from differences between populations. Thus, it is clearly worthwhile to collect from a number of populations in a region, not just one.
- Secondly, the variation between families within populations (sites) was generally less than that between populations. Despite this, they argued that

Table 5.5 Mean values for fruit characters of origins in PORIM collection

Country	Duras				Teneras			
	<i>n</i>	Fruit wt	Nut wt	M/F	<i>n</i>	Fruit wt	Nut wt	M/F
Ivory Coast	782	6.9	4.0	42.2	237	6.2	2.2	64.5
Nigeria	595	8.0 ± 2.7	4.2 ± 1.5	47.3 ± 7.8	324	6.5 ± 2.0	1.9 ± 1.0	71.0 ± 9.8
Cameroon	53	10.3 ± 3.3	6.2 ± 2.2	40.0 ± 7.8	42	8.6 ± 2.8	3.2 ± 1.1	62.4 ± 7.6
Congo	233	14.2 ± 4.3	7.9 ± 2.5	43.9 ± 7.2	82	12.6 ± 4.8	4.3 ± 1.9	64.1 ± 13.1
Tanzania	42	16.9 ± 4.1	8.9 ± 2.7	46.7 ± 10.1	17	15.5 ± 5.2	–	70.6 ± 8.8
Angola	42	14.2	–	48.9	12	11.7	–	70.9
Madagascar	17	–	1.8 ± 1.0	–	0	–	–	–
Senegal	104	2.6 ± 0.7	1.7 ± 0.6	35.2 ± 6.6	0	–	–	–
Gambia	45	2.5 ± 0.6	–	33.5 ± 5.5	0	–	–	–
Guinea	58	6.4	–	35.0	3	–	–	–
Sierra Leone	52	5.6	–	34.8	3	–	–	–
Ghana	–	6.4	–	39.7	–	–	–	66.0

From Rajanaidu and Jalani (1994a); data for Ivory Coast from Meunier (1969).

Data are means ± SD.

M/F: mesocarp/fruit.

up to 20 palms per population should be sampled, to ensure that genetic variation within the population is represented.

- As expected with a cross-pollinating species, most of the variation was between individuals within families. This does not mean that sampling from a number of palms and populations is not worthwhile; genetic theory predicts that this variance component will be large, even for characters with high heritabilities, although expected values depend on whether the families consist of half-sibs or full sibs. In addition to genetic variation, this component includes effects of any environmental differences between palms within the evaluation trial.

The information from these and similar analyses was used to plan the sampling for subsequent prospectings, the aim being to maximise the amount of diversity represented per sample collected. In 1984, collections were made in Cameroon and Congo, jointly between PORIM and Unilever plantation companies in those countries (Rajanaidu, 1986a). Material from these collections was planted in Malaysia and Colombia, as well as in the countries of origin. Collection in Tanzania and Madagascar (Rajanaidu, 1987) and in coastal parts of Angola (Rajanaidu *et al.*, 1991) followed in the late 1980s, and in Senegal, Sierra Leone, Guinea, Gambia and Ghana in the 1990s (Rajanaidu and Jalani, 1994a; Rajanaidu *et al.*, 2000a).

As a result of Rajanaidu's work, MPOB has established a collection of material that comprehensively

covers the entire oil palm belt of West and Central Africa. Fruit characters for the different countries represented are summarised in Table 5.5. The Nigerian material was similar to that surveyed by Meunier (1969) in the Ivory Coast, although mesocarp/fruit was higher in Nigeria. The Cameroon, Congo, Tanzania and Angola material had much greater fruit weights and nut weights than that from Nigeria or Ivory Coast. Fruit weights from Senegal and Gambia, and nut weights from Madagascar, were much smaller than from elsewhere, and mesocarp/fruit was very poor in Senegal, Gambia, Guinea and Sierra Leone.

Tanzanian *teneras* were described by Blaak as having 'paper thin' shells (Richardson, 1995), but the mesocarp/fruit figures in Table 5.5 are no higher than for the Nigerian material. Family mean shell/fruit figures from a trial with the material in Malaysia were not particularly low (trial mean 16.2% shell/fruit for *teneras*), although one palm with only 2.8% shell/fruit was identified (Kushairi *et al.*, 2000).

The extensive series of papers describing results of trials with the Nigerian material has already been mentioned. Rafii *et al.* (2000) gave results of trials with the Cameroon and Congo collections, and Kushairi *et al.* (2000) gave data from the trials with Tanzanian and Angolan material.

5.1.7.3 Collection of *Elaeis oleifera*

As discussed further in Section 5.5.1.6, there has been much interest in interspecific hybrids between

E. oleifera and *E. guineensis*. At least until MPOB's work on *E. guineensis* started, oil palm breeders had put much more effort into collection of *E. oleifera* than *E. guineensis*, and useful collections have been established in Malaysia, Ivory Coast, Costa Rica, Brazil and elsewhere (de Blank, 1952; Meunier, 1975; Escobar, 1982; Ooi *et al.*, 1981; Barcelos *et al.*, 1986; Miranda Santos *et al.*, 1986; Richardson, 1995). Despite these collections, many of the hybrids studied in Malaysia have been derived from a single palm of uncertain origin, but possibly from Brazil, known as the KLM palm (Kuala Lumpur Melanococca, *E. melanococca* being the old name for *E. oleifera*).

The MPOB prospection programme has been extended to cover *E. oleifera*, as well as some other oil-bearing palm species (*Jessenia* spp., *Oenocarpus* spp., *Bactris gasipaes*; Rajanaidu and Jalani, 1994a). *Elaeis oleifera* was collected in Colombia, Panama, Costa Rica, Honduras, Nicaragua, Brazil and Surinam (Rajanaidu, 1986b). The material from Brazil and Surinam gave much lower FFB and oil yields than the other origins, although the Brazilian material had higher oil/bunch than the rest (up to 7% oil/bunch in the best individuals; Din and Rajanaidu, 2000). The iodine value (Section 5.3.7) was lower for the Brazil and Surinam material than for other origins.

Barcelos *et al.* (2002) used molecular markers (Section 5.2.8) to study genetic diversity in *E. oleifera*, and identified four geographically distinct populations: Brazil, Peru, Central America/North Colombia and Surinam/French Guiana. In Brazil, Moretzohn *et al.* (2002) found more variation within populations than between, as was seen for *E. guineensis*; similarities were consistent with dispersal along the Amazon river network.

5.1.7.4 Utilisation of germplasm collections

Two different approaches to the use of prospection work have been adopted. The IRHO (now CIRAD-CP) has concentrated on introducing new sources of variation into existing breeding populations. Thus, Meunier (1969) studied a number of natural populations *in situ*, and selected parent palms from that population (Yocoboué) which would best complement the La Mé material in terms of fruit composition. The prospection in Cameroun appears to have followed the same strategy, with the Widikum population being selected (Cochard *et al.*, 2000). This strategy should be cost-effective, and quite satisfactory provided that there is no risk of the wild palm groves being destroyed or replanted with improved (and genetically restricted) seed.

MPOB, in contrast, has aimed to collect representative samples from all across the oil palm belt, sampling being done at random, to try to capture the full range of genetic variation present. These collections have then been planted at a research centre, where they will remain as a source of germplasm, even if the wild groves are lost. This strategy is more expensive (the MPOB Nigerian collection alone occupied 200 ha), but allows more detailed evaluation, not only for traits currently of interest, but also for others that may become important in future. The best material from the MPOB Nigerian collection is now being introgressed into existing breeding programmes (Rajanaidu *et al.*, 1989, 1998a; Chin and Shuhaimi, 2000), with particular emphasis on short stems (Section 5.3.4), a more liquid oil composition (Section 5.3.7.2), high carotene content (Section 5.3.3.3) and high kernel yield (Section 5.4.1.2).

5.1.7.5 Conservation of breeding populations

Rosenquist (1986) argued that preservation of BPROs as 'pure' populations was desirable, but was unsure whether this needed to be done by random crossing among 'unimproved' ancestral palms, where available, or whether the maintenance of a pure but continually improving breeding population would be adequate. There is little doubt that genetic variation is gradually lost under selection in a pure breeding population. Thomas *et al.* (1969b) showed that there was very little additive variation left in the Ulu Remis Deli *dura* BPRO, and Okwuagwu (1993) noted very little genetic variation among crosses in the Serdang Avenue BPRO. Rosenquist (1986) showed a significant level of inbreeding in Deli material in the Dami programme, and Mayes (1995) found a loss of heterozygosity in successive generations of AVROS material. Thus, if the aim of conserving BPROs is to preserve genetic diversity, random crosses appear necessary, among palms as close to the unimproved base population as possible. There is little published evidence that such crosses are being made in BPROs, but in the PORIM Nigerian collection, conservation is already in progress. About ten trees per population are selected randomly, to make five bi-parental crosses, with 20 seedlings from each cross being planted. Interpopulation crosses are avoided, to ensure that any coadapted gene complexes within populations remain intact (Rajanaidu *et al.*, 2000b).

An alternative to random crosses would be to use molecular markers to identify palms covering the full range of genetic diversity within the BPRO (Section 5.2.8.2). Marita *et al.* (2000) proposed that the 'genetic distances' between all individuals in the population

should be calculated from marker data; the more markers in common between two palms, the smaller is their genetic distance. The palms selected for conservation should then all be separated by more than a minimum distance, the minimum being calculated from the total variation in the population. Toro *et al.* (1999) recommended using markers to maximise heterozygosity in a conservation programme.

5.2 TECHNIQUES USED IN OIL PALM BREEDING AND SELECTION

To select individual palms for breeding it is necessary to measure their bunch yield, and to analyse the bunches for their oil and kernel content; vegetative measurements are also sometimes used. To breed from selected palms controlled pollination must be undertaken, and the progenies produced must be planted in statistically valid experimental designs. Chin (1999) gave a general review of pollination and recording methods.

5.2.1 Controlled pollination

The production of plants of known parentage is a laborious procedure in the oil palm (Plate 5.4). The female

inflorescence has to be isolated, pollen has to be collected from a male inflorescence and the cross made without contamination, and the resulting bunch and seeds must be kept clearly identified through germination and the nursery to the field.

5.2.1.1 The need for controlled pollination

In the early days of oil palm breeding, before the discovery of the inheritance of fruit form by Beirnaert and Vanderweyen (1941), many bunches said to be from controlled pollination were probably in fact out-pollinated, owing to the crude methods used or lack of supervision. Illegitimacy in the ancestry of AVROS *pisiferas* has already been mentioned (Section 5.1.1.3). Since 1941, when crossing *dura* with *tenera* or *pisifera*, *tenera* with *tenera*, or *tenera* with *pisifera*, the segregation of fruit forms in the progeny (Section 5.3.3.1) has provided a check on the work done (although not until several years after planting). Until the advent of molecular markers, however (Section 5.2.8), it was not possible to detect pollination errors in $D \times D$ crosses.

With good control, it is possible to keep the percentage of illegitimate *duras* in a $D \times P$ cross below 1%. In Malaysia, such figures were regularly obtained up until the early 1980s, but following the introduction of the



Plate 5.4 Controlled pollination. (A) Pollinator with bag for isolating the inflorescence; (B) spraying formaldehyde to kill extraneous pollen before pollination takes place.

pollinating weevil (see Section 2.2.2.5), contamination became a serious problem for some seed producers (Rao *et al.*, 1994), with nearly 20% *duras* being found in some blocks. *Elaeidobius kamerunicus* is apparently more persistent in its attempts to reach anthesising female inflorescences than *Thrips hawaiiensis*, the pollinating agent in the Far East before 1981, and stricter controls had to be adopted after the introduction. Kushairi and Rajanaidu (2000) indicated that this problem is now mostly under control, although contamination still occurs occasionally.

5.2.1.2 Methods of controlled pollination

The essential requirements for controlled pollination were listed by Donough *et al.* (1992), Chin (1999) and Rao and Kushairi (1999), who described the quality control procedures needed to ensure that pure seed is produced. Asmady *et al.* (2002) outlined a quality control system supported by ISO 9001 certification. Essential points are listed below; steps to exclude the pollinating weevil, *Elaeidobius kamerunicus*, are particularly important.

Collection and storage of pollen: The male inflorescence must be bagged 7 days before the flowers open. The spikelets must be thoroughly sprayed with a formaldehyde solution, to kill any foreign pollen or insects adhering to the spikelets. In the bagging operation a collar of cotton wool, sprayed with a contact insecticide, is placed around the inflorescence stalk, and the mouth of the bag is tied over this collar with strong twine or wire. When the inflorescence reaches anthesis, as seen through an observation window in the bag, the whole inflorescence is cut, still in its bag, and removed to the laboratory, where it should be inspected for signs of damage, or *E. kamerunicus* within the bag, and rejected if either is found (Donough *et al.*, 1992).

In a breeding programme, pollen may need to be stored for several months. Some of the earliest work on pollen storage appears to have been done by Prendergast (internal Unilever reports, 1952, 1953). Pollen may be stored satisfactorily over calcium chloride or silica gel at tropical room temperatures for 6–8 weeks. This period may be extended to a year or more by storage at 5°C or in a partial vacuum (Henry, 1959; Devreux and Malingraux, 1960). For longer term storage, vacuum drying may be used (Hardon and Davies, 1969; Bénard and Noiret, 1970); the pollen is sealed in ampoules and stored in a deep freeze at –18°C.

Preparation and pollination of the female inflorescence: A female inflorescence should be bagged at least 1 week before the first flowers are expected to open. It is sometimes necessary to enclose the bag in wire netting to

prevent damage by rats or squirrels, but old fertiliser bags may be adequate as outer bags, as they appear to have a repellent effect (Donough *et al.*, 1992). Labelling is done at the time of bagging, with the pollination particulars added at the time of pollination.

Before pollination, the inside of the bag should be inspected for weevils, as far as is possible using a torch light through the window. If weevils are seen, the inflorescence should be discarded. The pollinator sprays the bag with formalin, and pollen is then blown in from a glass tube or plastic wash bottle, through a hole cut in the celluloid inspection window. The hole is then sealed with adhesive tape. The receptive period for female flowers normally lasts for 36–48 h, with flowering starting at the base of the inflorescence and progressing to the top. Usually, therefore, if pollination is repeated on three successive days, good fruit set will result. The bag should be inspected for weevils the day after the last pollination.

For safety, the bag should be left on the bunch for 3–4 weeks after pollination. The bag should be inspected after 10 days for damage; if it is damaged, the inflorescence is discarded. According to Donough *et al.* (1992), it is normal for up to 15% of bagged female inflorescences to be discarded at some stage; these authors indicated that, with strict quality control, more than 99% *teneras* can be obtained from D × P crosses. On some palms, the ‘accompanying male flowers’ (see Section 2.2.2.2) may produce pollen, so unwanted self-pollination is a possibility.

Blank pollinations: As a check on the reliability of the work, some inflorescences may be pollinated with dead pollen, without the workers being informed. These control bunches are harvested later and inspected for any signs of fruit set. Hartley (1988) recommended that such bunches should be sprayed with a 100 ppm solution of 2,4,5-T, to induce parthenocarpic development of unfertilised fruits. This ensures that the bunch as a whole will develop; bunches with very few fruits usually fail to ripen, so without the 2,4,5-T treatment any fruits from flowers that had been fertilised might rot before they were seen.

Management of seed parents: Palms being used as seed producers need a good deal of attention to facilitate pollination. Old leaf bases and debris have to be removed, and the fibres and spines on the leaves subtending or near the bunch need to be cut away, so that the pollinator can access the bunch without injury. As little damage as possible must be done to the leaves, since any pruning would be likely to reduce further female inflorescence production. To maximise bunch production by selected palms, they may be given extra fertiliser, and leaves of neighbouring palms may be cut back to reduce

competition. Irrigation, with a tractor-drawn tank, has also sometimes been done; with the high value of oil palm seeds, very few extra seeds are required to cover the costs of such operations.

5.2.2 Trial designs and crossing programmes

Oil palm breeding trials are usually planted in standard statistical designs [completely randomised or randomised complete block design (RCBD)]. Soh *et al.* (1990) compared the precision of 30 different trials in Malaysia. Most trials had four or five replications of ten-, 12- or 16-palm plots, and typically could only detect differences between families of 15% or more. In order to detect differences of 10%, plots of 12 palms with five replications, or 16 palms with four replications, were required on coastal soils. On the more heterogeneous inland soils, 20-palm plots with five replications, or six or more replications of smaller plots, would be needed. Completely randomised and cubic lattice designs did not have any advantage over RCBD, nor did covariance adjustment using the yields of neighbouring plots make much difference. If single-palm plots were to be used, it appeared that the number of replicates would need to be very large, so that the total number of palms was much the same as for designs with larger plots and fewer replications.

Breure and Konimor (1992) also considered the optimum plot size for oil palm breeding trials. Using data from trials in PNG, and a theoretical model of interpalm competition developed by the late C.J.T. Spitters, they concluded that the response to selection would be greater with eight- or 16-palm plots than with the same number of palms in single-palm plots. This was because interpalm competition introduced less bias with the larger plots.

Perhaps because triangular (hexagonal) planting is the norm for oil palms, the honeycomb design of Fasoulas (1979) has often been used by oil palm breeders. This is a single-palm plot layout, with restricted randomisation, such that each of the seven families always has all the other six families as neighbours. More complex designs, on the same principle but with larger numbers of families, are also available. The design was claimed by Fasoulas to be good for adjusting for soil heterogeneity. Sterling *et al.* (1993) compared honeycomb and randomised block designs. No comparison of the statistical precision of the two designs was made, but for the first 8 years of production, the correlation of progeny FFB yields between the two trials was highly significant, and that for mean bunch weight significant,

but that for bunch number per palm was not significant. Correlations for trunk height and rachis length were highly significant, as were those for bunch components, with the exception of fruit/bunch. These results suggest, surprisingly, that the single-palm plot nature of the honeycomb design does not result in significant bias of results through interpalm competition, despite large differences in height between families in this study. However, this finding conflicts with the results of Hirsch (1980), who showed that yield of individual palms was positively correlated with palm height (Section 5.4.4).

Before making any decisions on the design of the field trial, the breeder must first decide on the arrangement of crosses between the selected parents: the crossing design. The North Carolina models, NCM1 and NCM2 (Comstock and Robinson, 1952), have been widely used by oil palm breeders, particularly for *pisifera* progeny testing. In the NCM1 design, each *pisifera* is crossed with a different set of *duras*; because the same *dura* need not be used more than once, crossing is quickly completed, and if there is little variation between the *duras*, the design gives satisfactory estimates of the performance of *pisifera* parents. However, crossing designs in which all male parents are 'connected' through common female parents allow breeding values to be estimated (Section 5.4.3). For this reason, the NCM2 design, in which each *pisifera* is crossed with the same set of *duras*, is preferable, but the need to make several crosses with each *dura* can extend the time required to complete the crossing programme. Other connected designs can also be used; Breure and Verdooren (1995) advocated 'alpha' designs, in which breeding values of all parents are estimated with approximately equal statistical precision, with each *dura* being used for only two crosses.

5.2.3 Yield records and generation time

The recording of bunch yield presents no real problems, but efficient supervision is essential to give reliable data. Harvesting must be regular and a fixed standard of ripeness should be adopted. Bunches are normally weighed at the foot of the palm. The date of harvest, the palm number, the number of bunches (occasionally more than one bunch is ripe on a single palm on the same day) and the weight of the bunch or bunches must all be recorded. Field records are usually hand-written, with the data being later transferred to a computer, but hand-held data loggers have obvious advantages in terms of avoiding transcription errors.

Bulk recording of plot yields has been suggested (Breure and Verdooren, 1995). This should be

cost-effective for clone trials or agronomy trials, where it is only the plot yield that is of interest, but in breeding trials, individual palm data are usually required for selection. In $D \times P$ progeny tests, mean yields of the progenies are used to identify the best parents, so individual palm data are not necessary; however, such progeny tests may also be used as sources of ortets for clonal propagation, and bulk recording would then not be satisfactory, as individual palm data would be needed.

The minimum duration for which yields must be recorded depends to some extent on the objective, but is always several years; individual palm yields vary greatly from year to year, and data from a single year may mean very little. Haines and Benzian (1956) indicated that little reliance could be placed on results over less than 3 years. Corley *et al.* (1988) found significant clone $\times$ year interactions and concluded that at least 5 years' records would be needed to give reliable mean yields from clone trials.

Blaak (1965) showed that yield over the first 4 years was highly correlated with yield from the 11th to 16th years. Okwuagwu and Tai (1995) showed that heritability (Section 5.2.6.2) of FFB yield and its components was low if based on single years. Means for several years gave higher heritabilities, and a plateau value was approached after 3–4 years for yield and bunch number, and 6 years for mean bunch weight. Most oil palm breeding trials are recorded for the first 4 or 5 years of production only, selection being done at the end of that period. Sometimes, up to 10 years' records may be used (e.g. Dumortier, 2000). Reliable family mean yields can probably be estimated from a shorter period of recording than individual palm yields. In Malaysia, the Standards and Industrial Research Institute of Malaysia (SIRIM) standard for commercial seed production requires that *dura* parents be recorded for a minimum of 4 consecutive years.

The duration of yield recording is one of the factors determining the time required to move through one generation of a breeding programme. Table 5.6 shows that, from the date that the controlled pollination is

done, it takes at least 8, and perhaps nearer 10 years before recording is complete and palms can be selected for the next phase of the programme. Various attempts to find methods of early selection have been made, without much success (Section 5.2.7). One of the more promising approaches is the use of DNA markers (Section 5.2.8), but these are still at the experimental stage.

5.2.4 Bunch analysis

The aim of bunch analysis is to estimate the oil and kernel contents of bunches, so that yields of oil and kernel can be calculated. The standard bunch analysis procedure is the NIFOR method, described by Blaak *et al.* (1963); this involves a series of sampling steps, commencing with the whole bunch and finishing with a few grams of dry mesocarp for determination of oil content. The layout of a bunch analysis laboratory and the steps in the process are shown in Fig. 5.6, and the process is detailed in Section 5.2.4.1.

The NIFOR method has been in general use for nearly 40 years, in many different research centres. Inevitably, some variations, in terms of sampling methods, sample weights and methods of preparation, have been introduced. A detailed study of biases and errors arising from differences in method was undertaken in Malaysia in the 1980s, with results summarised by Rao *et al.* (1983). Important points emphasised by these authors and others are listed in Section 5.2.4.2. Corley (1998) showed that correlations between oil/bunch for the same groups of families measured in different laboratories were positive and usually statistically significant, but mean values might differ considerably. It was not possible to separate differences due to environment from the effects of bias in the laboratory methods. A general conclusion from this work is that comparisons between bunch analysis data from different laboratories will rarely be reliable. This is not a problem for the practical plant breeder, who will primarily be concerned with relative differences between palms analysed in his own laboratory.

Table 5.6 Time scale for oil palm breeding

Operation	Time (months)	
	Duration	Completion
Controlled pollination	0	–
Development of bunch to harvest	5	5
Germination	4	9
Nursery	12–15	21–24
Immature period in field	27–30	48–54
Yield recording and bunch analysis	48–60	96–114

5.2.4.1 The NIFOR method

After harvest, bunches are normally weighed at the foot of the palm, and marked or labelled there with the palm number before they are removed for analysis. The number of detached fruit should be recorded, and the fruit carried with the bunch. Fruit form should be determined on arrival at the laboratory, where the bunch is weighed again, and the spikelets are removed and weighed; the stalk is also weighed, before it is discarded. A random sample of spikelets is taken and weighed, and

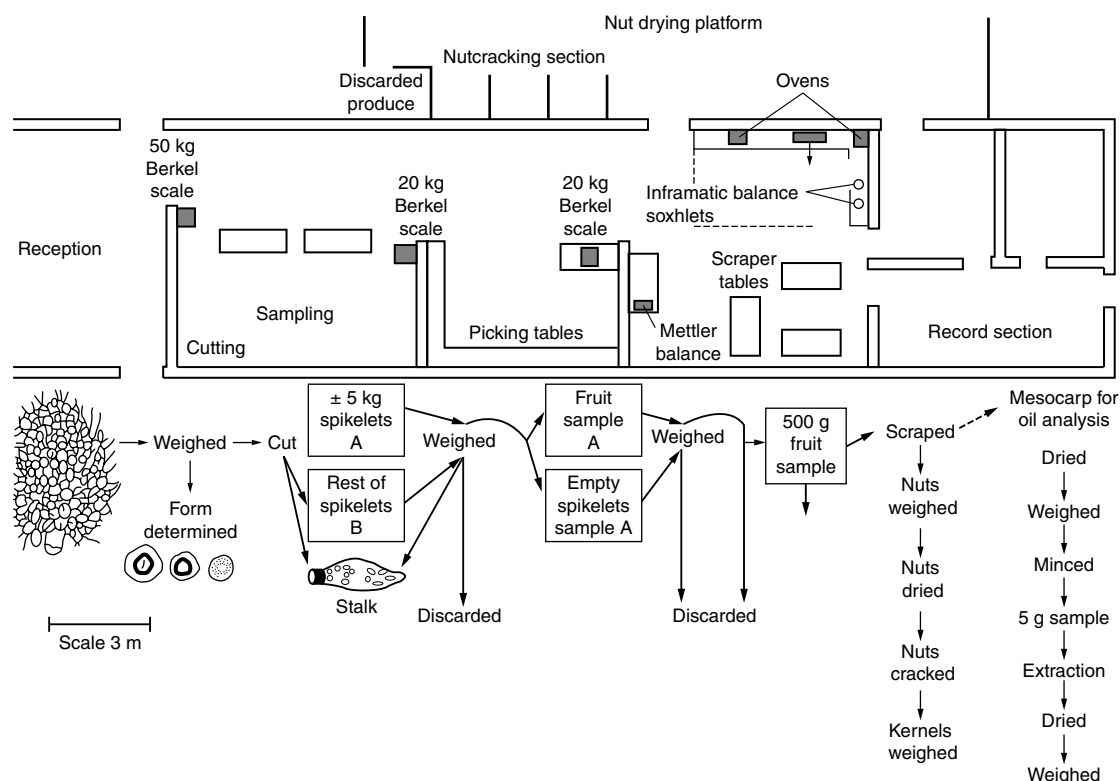


Fig. 5.6 Plan of a bunch analysis laboratory, with a diagrammatic representation of the process.

the fruits are removed and weighed. This gives the ratio of fruit weight to spikelet weight of the sample, and as the total weight of spikelets from the bunch is known, the fruit to bunch weight ratio (F/B) can be calculated. All weights are normally recorded on a card, which accompanies the samples through the process.

A sample of normal fertile fruits is then taken from those removed from the spikelet sample, weighed, and the mesocarp scraped off. The nuts are weighed, the weight of mesocarp calculated by difference, and hence the 'wet' mesocarp to fruit ratio (WM/F) can be calculated. A sample of the mesocarp is then taken, weighed, oven-dried and weighed again; this gives the dry matter content of the mesocarp (DM/WM). Finally, a solvent is used to extract the oil from a sample of the dry mesocarp, to give the ratio oil to dry mesocarp (O/DM). The last two ratios are often multiplied together to give oil/wet mesocarp (O/WM), but in breeding work it is probably useful to consider the two components separately. Oil to bunch is calculated from:

$$O/B = O/DM \times DM/WM \times WM/F \times F/B \quad (5.1)$$

Some laboratories multiply the figure obtained by a correction factor (usually 0.85), to obtain an equivalent to factory oil extraction ratio, allowing for factory losses.

After removal of the mesocarp, the nuts are air dried for about 3 days to facilitate cracking. The shell is removed and the kernels are weighed, so the kernel to fruit ratio (K/F) can be calculated. Shell weight, and hence shell/fruit (S/F), is usually calculated by difference between kernel weight and nut weight, but note that the moisture lost from the nuts during drying will be included in this difference. Kernel to bunch (K/B) is calculated from:

$$K/B = K/F \times F/B \quad (5.2)$$

5.2.4.2 Variations on the method

We discuss bunch analysis methods in some detail here, because accurate determination of oil/bunch is such an important aspect of oil palm research, but is not dealt with in standard field manuals. The review of methods by Rao *et al.* (1983) has already been mentioned. Lim and Toh (1985) showed that there could be systematic

positive errors at the successive sampling stages in the standard method, because moisture losses were not adequately allowed for. As noted above, F/B is calculated from spikelets/bunch and fruit/spikelets ($F/B = Sp/B \times F/Sp$), F/Sp being measured on a sample of spikelets. If total spikelet weight is measured immediately after chopping the bunch, but weight of the sample only after 3 days' drying (see below), then the calculation becomes $Sp_1/B \times F/Sp_2$; Sp_1 and Sp_2 are not equal, so do not cancel out mathematically to give a correct F/B estimate. Moisture loss cannot always be avoided, but steps can be taken to ensure that it does not introduce bias in the results. Ismail *et al.* (1985b) proposed correction factors to be used to allow old, biased data to be compared with data from an improved bunch analysis method. Sharma *et al.* (1999) suggested that the standard method systematically overestimated the oil content of large bunches.

Sampling of bunches: The first stage is to decide which bunches to analyse; it is not feasible to analyse all bunches from a large breeding trial. A fairly standard procedure is to analyse a random sample of about 30 bunches per family, usually over 2 or 3 years, to estimate family mean oil and kernel to bunch, but the make-up of this sample of bunches has received little attention. Theoretically, it would be best if palms were sampled in proportion to their yield, so that the highest yielding palms contributed most to the mean, but 30 bunches is usually too few to allow such a weighted sampling. The family means will be used to identify the best families, and then more bunches will be sampled from all palms in those families, usually up to a minimum of five bunches per palm. Dumortier (2000) showed the increase in heritability that resulted from increasing the number of bunches analysed per palm, and suggested that five or six bunches per palm were sufficient. If bunches from different families are analysed at different times, it may be desirable to make adjustments for seasonal effects; Dumortier *et al.* (1992) adjusted individual bunch data in the Congo for both month and year of sampling.

Ripeness standard: Oil content continues to change during the time when harvesting is normally done (see Section 10.4.4). Rao *et al.* (1983) showed significant differences in O/M and O/B between bunches harvested at five loose fruit per bunch, and three to five loose fruit per kilogram. Thus, it is important to try to harvest at a uniform standard, and to record the number of detached fruit.

Bunch weight: Moisture loss between harvest and delivery to the bunch analysis laboratory can be significant; over a 24 h period, losses of 2–14% of bunch weight were recorded. Consideration of Equation 5.1

shows that loss of moisture may mean that some of the intermediate ratios are biased, but provided that the original bunch weight (before moisture loss) is used, O/B , the product of all the ratios, should not be affected. If, for example, the mesocarp loses moisture, WM/F will be too low, fruit weight will be underestimated, so F/B will also be too low, but DM/WM will be overestimated. These errors will cancel each other out, and O/B should still be accurate, if the oil content of the dry mesocarp is accurately measured. If bunch weight after moisture loss is used, although the weight of oil per bunch will still be accurate, the O/B ratio should not be applied to field FFB data, where there is no moisture loss.

Spikelet sampling: The standard method is to mix the spikelets thoroughly after chopping, and then to take a random sample. Both the sample and the remainder of the spikelets must be weighed at this stage, so that, if there has been any moisture loss, it is the same for the sample and the total. Some laboratories have adopted 'stratified' sampling methods. Either the tips of a spiral of spikelets are marked with paint before chopping, with these marked spikelets then being used for the sample, or separate samples are taken from the apex, middle and base of the bunch. A comparison of F/B estimates with true values obtained by stripping the entire bunch showed that random sampling of spikelets is essential; the stratified sampling methods tended to overestimate F/B , by up to 10%.

Fruit stripping: Fruit separation from fresh spikelets is tedious and time consuming. If spikelets are stored for up to 3 days, many fruits detach naturally, and the remainder are easily removed manually. During storage, both fruit and spikelet tissue lose moisture: over 3 days, fruit lost 2–3% in weight, whereas the empty spikelets lost up to 13%. Because most of the loss is from the spikelets, the resulting bias in F/B estimates will not be very large, if fruit weight is expressed relative to the original spikelet sample weight, before storage.

On the spikelets there will be found fully fertile fruit, parthenocarpic fruit, which contain oil but no nut, and infertile fruit (undeveloped flowers), which are small and colourless and contain no oil. The last are included in the weight of the empty spikelets. Fertile and parthenocarpic fruit are sometimes estimated and their composition is analysed separately, particularly where the proportion of parthenocarpic fruit is high, as it often is in *E. oleifera* $\times$ *E. guineensis* hybrid bunches.

Fruit sampling: After stripping, a fruit sample should be taken immediately (to ensure that sample and total have suffered the same degree of moisture loss) for determination of fruit composition. Blaak *et al.* (1963) recommended a 500 g sample; according to Rao *et al.*

(1983), 250 g is sufficient, but they recommended a sample of 25 or 30 fruits, rather than a specific weight. Because the aim in breeding work is to estimate the genetic potential of a palm, it is accepted practice to replace any damaged fruits in the sample by undamaged fruits of the same size. However, any non-random selection tends to result in a biased fruit sample, with a greater average fruit weight than that for the total mass of fruits. One way to avoid this is to weigh and count the total fruits after stripping, to weigh the sample, and then to reject and resample, if the average weight of the sample is more than a few per cent different from the average for the total.

For very large bunches, Sharma *et al.* (1999) advocated analysing separate samples of outer, middle and inner fruit, and taking averages for WM/F and O/WM weighted according to the proportions of outer, middle and inner fruit in the whole bunch. For bunches with a high proportion of parthenocarpic fruit, such as those from interspecific hybrids, it may also be worth taking separate samples of normal and parthenocarpic fruit.

Mesocarp removal: This process, often called depericarping, is usually done manually, with a sharp knife. Ismail *et al.* (1985b) noted that oil could be absorbed by the gloves used to protect workers' hands during this operation. The sliced mesocarp loses moisture rapidly, and care must be taken to avoid erroneous data as a result. The recommended approach is to weigh the nuts after depericarping, and to calculate the weight of fresh mesocarp by difference; thus, partial drying of the mesocarp during the process does not matter and drying of the nuts is negligible over such a short period. All the mesocarp must then be retained and dried, so that DM/WM can be calculated, as any mesocarp lost would be counted as moisture loss in the calculations.

Ooi and Tam (1976) investigated the possibility of taking slices of mesocarp for oil determination, before the depericarping operation, but variation in oil content between different regions of the mesocarp precluded this. Some laboratories have taken subsamples of fresh mesocarp for drying, but moisture losses during depericarping make this an inaccurate method.

Mesocarp drying: Drying is done in an oven at 105°C for 24 h, or in 10 min in a microwave oven (Yáñez *et al.*, 2000). Thin slices of mesocarp dry more quickly than minced mesocarp (Rao *et al.*, 1983). After drying, the mesocarp is ground in a food blender, prior to oil extraction. Sieving through 3 mm mesh after grinding, to remove larger, unground pieces, led to more efficient oil extraction (shorter time to complete extraction), without introducing a bias (Rao *et al.*, 1983).

Oil extraction: The most widely used method is Soxhlet extraction, with hexane or petroleum ether. Samples of dried mesocarp between 2.5 and 10 g are used. Hartley (1988) recommended duplicate samples, with duplicates differing by more than 3% being discarded, but Rao *et al.* (1983) showed that results were highly repeatable and suggested that duplication of samples was not necessary.

Blaak (1970a) developed a method of cold extraction, which was claimed to be cheaper than Soxhlet extraction. In the simplest adaptation of this method, a set of samples, in a basket, is put to soak in a bucket containing the oldest solvent; the basket is then lifted, drained and transferred to the next oldest solvent, and so on, with the final stage being in fresh solvent. Blaak showed that oil/mesocarp figures obtained by this method compared well with Soxhlet extraction. Petrol can be used, being much cheaper than other solvents, and 50 g samples of mesocarp can be extracted, instead of the 5 g samples normally used with the Soxhlet method.

A method of measuring mesocarp oil content by specific gravity determinations has been used in some laboratories. A known weight of solvent of high specific gravity is added to a weighed sample of dried mesocarp and the mixture is ground in a high-speed blender. The oil and solvent are then filtered, and the specific gravity of the filtered mixture is measured. This depends on the amount of oil in the solvent and hence in the original sample. The solvent used must have a specific gravity as different from that of the oil as possible; ortho-dichlorobenzene, with a specific gravity of 1.3, is recommended. This 'Oléometre' method is not as accurate as Soxhlet extraction, and tends to give slightly lower O/DM figures, but it has the advantage that a large number of determinations can be completed in a relatively short time. By doing occasional Soxhlet extractions as well, corrections can be made, but for comparative purposes the Oléometre method is quite satisfactory (Servant and Henry, 1963).

The earliest method of estimating mesocarp oil content was the 'indirect method', based on the assumption that fibre content of the mesocarp is constant, so that a linear relationship exists between moisture content and oil content. Thus, DM/WM was measured, but not O/DM, so oil content could be estimated by drying alone. Various formulae have been put forward, the first, from Vanderweylen *et al.* (1947) in the Congo, was:

$$O/WM = 87.4 - 1.08 \times (100 - DM/WM) \quad (5.3)$$

Later investigators in West Africa recognised the method to be approximate and considered the

following equation, which assumes a constant fibre percentage of 16, to be satisfactory (Desassis, 1955; Chapas *et al.*, 1957):

$$O/WM = 84 - (100 - DM/WM) \quad (5.4)$$

No significant difference was found between the mean fibre content of *dura* and *tenera* pulp. Studies in West Africa (Blaak *et al.*, 1963) showed that there can be differences between progenies of 2–3% in the fibre content of mesocarp, and that seasonal variation within progenies can be even greater. The indirect method was therefore considered unlikely to be sufficiently accurate for regular use in selection and breeding, and was abandoned. It might be useful for agronomy trials, however, where a mixture of genotypes is involved, and it has recently been advocated for ‘factory gate’ monitoring of ripeness (Yañez *et al.*, 2000), using a microwave oven for rapid drying. These authors found:

$$O/WM = 82.4 - 0.95 \times (100 - DM/WM) \quad (5.5)$$

For a typical value of DM/WM of 70%, these three equations give O/WM ranging from 54 to 55%. The choice of equation is probably not very important, therefore, but the question of whether or not the fibre content is constant is critical. Wonkyi-Appiah (1982) showed that a ‘modified indirect method’, using the progeny mean fibre content instead of the 16% assumed in Equation 5.4, gave good correspondence with the Soxhlet method for individual palms.

Nut composition: After depericarping and weighing, with the NIFOR method the nuts are air-dried for 3 or 4 days to facilitate kernel separation after cracking. The kernels are weighed and the shell weight is determined by difference from the original nut weight. Kernel to fruit and shell to fruit percentages may thus be obtained. This is not an entirely accurate method, as the kernels lose

weight during the drying process, so that K/F may be underestimated and S/F overestimated.

Mollegaard (1970) tried drying the nuts in an oven at 80°C for up to 5 h. This was sufficient to make cracking much easier. As Table 5.7 shows, the shells were closer to dryness after this period than the kernels, particularly with *tenera* nuts, but moisture loss from kernels was significant, and K/B would be underestimated.

Rao *et al.* (1983) recommended complete nut drying at 105°C overnight, and correction of the calculated K/F percentage to commercial moisture levels by adding 7%. This gives an accurate figure for kernel yield and avoids the problem of different rates of moisture loss, but if shell weight is calculated by difference, S/F will not be accurate. Shell is not a commercial product, so it might be thought that this does not matter, but plant breeders often put considerable emphasis on (low) S/F in selection. The best approach may be to weigh the shell as well as the kernels, and to use dry shell/fruit as a selection criterion if required. It should then be recognised that mesocarp, shell and kernel percentages will not total 100, as there will also be moisture loss from the nuts.

5.2.4.3 Future developments

Hartley (1988, p. 210) quoted a labour requirement for bunch analysis of less than 0.2 man-days per bunch, excluding oil determination, but with increasing labour costs, there must be scope for a mechanised bunch analysis system. Some work on this is in progress (V. Rao, pers. comm., 2000). Reduced costs would allow more bunches to be sampled; 30 bunches, from a family of, say, 48 palms, over a period of 3 years, is probably less than a 5% sample. A mechanised method might also permit whole-bunch analysis; the present procedure is such that a bunch that may weigh over 20 kg is finally represented, after three subsampling stages, by a 5 g sample of dried mesocarp for the determination of oil

Table 5.7 Moisture contents of shell and kernel, before and after 5 h oven drying at 80°C

	Moisture content (% dry wt)		Loss in weight (% fresh wt)	Moisture lost (% of initial)
	Before drying	After drying		
<i>Dura</i> shells	18.9	7.8	9.3	58.7
<i>Dura</i> kernels	35.3	25.6	7.1	27.5
<i>Tenera</i> shells	23.3	6.7	13.5	71.2
<i>Tenera</i> kernels	39.9	21.4	13.2	46.4

Calculated from Mollegaard (1970).

content. The scope for sampling error is obvious. The key parameters are oil and kernel to bunch. Breeders also look at the constituent ratios, but if whole-bunch analysis on a larger sample of bunches could be done, the improved accuracy of the oil yield estimates should outweigh the loss of information on components. Chan *et al.* (1999) described a method involving grinding of dried mesocarp and shell, after cutting the fruit in half to remove the kernels. The advantage of the method was that mesocarp removal was avoided, but information on mesocarp and shell to fruit was lost. The authors claimed greater accuracy than the NIFOR method, but did not specify how the sampling was done for the latter.

5.2.5 Growth measurements

Methods of measuring vegetative growth, and of estimating dry weights from non-destructive measurements, are discussed in detail in Section 4.1.3. These methods were originally developed as selection tools for breeding trials (Corley *et al.*, 1971b; Hardon *et al.*, 1972), the aim being to try to move away from selection for yield per palm and to consider yield per hectare. Although selection might still be based on single palms, measurements of such characters as leaf area were expected to help in estimating potential yield per hectare. As discussed in Section 4.3.8, palms selected simply for high yield per palm were shown to be above average in vigour, and were presumably highly competitive (Corley *et al.*, 1971b; see also Sections 5.3.4 and 5.4.4). Breure and Corley (1983) showed that selection for high bunch index would give palms that were well adapted to high-density planting, and selection for high bunch index is now emphasised in several breeding programmes (e.g. Rosenquist *et al.*, 1990; Donough and Law, 1995).

5.2.6 Genetic analysis in breeding trials

If breeding is to be efficient and to make good progress, the breeder must understand the causes of variation in populations, and how characteristics are inherited. To this end, much work has gone into the genetic analysis of oil palm breeding trials. A good general reference to methods in quantitative genetics is Falconer (1981).

5.2.6.1 Causes of variation

There are essentially three sources of variation between individual plants: environment, genotype, and the

interaction between these two. The first of these results from differences in the microenvironment in which the plants are growing; for example, it may rain on one part of a large trial but not another. Soil fertility can differ widely from one planting point to the next, although the effect of this may be reduced because the extensive root system of the oil palm 'integrates' fertility over a larger area. Genotypic variation may result from the effects of single genes, as with shell thickness, or from the combined effect of many genes. Genotype $\times$ environment ($G \times E$) interactions occur when the performance of some genotypes is more affected by environment than others. A simple example of a $G \times E$ interaction could involve two palms with similar yield potential, but one susceptible and one resistant to a disease. In the absence of the disease, both would yield the same, but where the disease was prevalent, the resistant palm would yield more. This is a genetic difference, but only expressed in certain environments. $G \times E$ interactions are discussed in Section 5.5.1.7.

Genetic variation can be subdivided in various ways. It is useful to distinguish between factors controlled by single genes (or major genes), such as shell thickness (Section 5.3.3.1), and quantitative traits, resulting from the combined effect of many genes (polygenes or minor genes). In practice, though, the distinction between major and minor genes is not clear-cut. All genes segregate, according to Mendel's laws, in the discontinuous manner seen for shell thickness, yet most of the variation in natural populations appears continuous. As Falconer (1981) explains, there are two reasons for this: the first is the simultaneous segregation of many genes affecting the character. If the effect of some of these genes is of the same order as the error or the unit of measurement, the distribution will appear continuous; the distinction between genes concerned with qualitative characters and those causing quantitative variation thus lies in the magnitude of their effects. The second reason is the superimposition on the genetic effects of truly continuous environmental variation.

5.2.6.2 Heritabilities

Population geneticists subdivide the genetic variation in quantitative characters into a number of components. The most important division is between additive and non-additive variation. Additive variation is consistently transmitted from a parent to all of its offspring. It results from the summation of the effects of many minor genes, and is a large component of the variation in most characters. Non-additive effects, in contrast, may not be transmitted from parent to

offspring in a simple manner. Such effects may result from dominant and recessive genes (see Section 5.3.3.3 for an example), maternal inheritance, in which a characteristic is inherited only if it is carried by the female parent, 'epistatic interactions', in which one gene alters the expression of another, and various other effects. Most crossing designs allow additive and non-additive variance components to be estimated statistically. Such estimates of variance components are useful to the breeder, because additive variation is easily utilised (see Section 5.2.6.3), whereas non-additive variation may require a series of crosses before it is understood, let alone exploited.

The breeder is interested in the genotype of the palms, but what is actually measured is the phenotypic value or phenotype, which is affected by the environment, as well as by the genotype. The term heritability is used to describe the ratio of genetic variation to total phenotypic variation (genetic plus environmental). Heritability indicates the reliability of the phenotype as an indication of the genotype; possible values range between 0 (all variation environmental) and 1 (all variation genetic).

Two different terms are used: 'narrow sense' and 'broad sense' heritability. Narrow sense heritability is the likelihood that offspring will inherit a particular characteristic from their parents, or the degree of resemblance between relatives. It involves additive variation only, and can be calculated as the regression of offspring data on parental values; Fig. 5.7 shows an example. The heritability is equal to the regression coefficient (the slope of the line), when mean values for both parents are used. If only one parent is used (as would unavoidably be the case for fruit characters where male parents were sterile *pisiferas*, for example), the heritability is equal to twice the regression coefficient (see Falconer, 1981, for explanation). Thus, in Fig. 5.7, the heritability was 0.62.

Broad sense heritability includes all genetic variation, non-additive as well as additive. Non-additive effects may not be simply transmitted from parent to offspring, and may be difficult to exploit in a breeding programme, as already noted. However, a clone carries all the genes of the ortet from which it was derived, so breeders can make use of non-additive effects by clonal propagation of superior individuals. Thus, broad sense heritability is useful when considering the selection progress achievable through clonal propagation, and can be estimated from a regression of data from clones on their ortets (see Tables 5.9 and 5.15). This does not involve true inheritance from parent to offspring; heritability is used here to describe the ratio of genetic variation to total variation (genetic plus environmental).

It is important to remember that heritability is specific to the population and environment being studied. If environmental variation is large (because of poor trial design or poor choice of site, for example) heritability, as the ratio of genetic to total variation, may be low even if there is a great deal of genetic variation in the population. Conversely, if there is little genetic variation, heritability will remain low no matter how well-designed the experiment. Accuracy of measurement is also important, since, statistically, measurement error will be included in the environmental component. Dumortier (2000) emphasised the importance of repeating measurements sufficiently often to obtain reliable data. For these reasons, and also because the population sizes that can reasonably be studied with oil palms are too small to allow very precise estimates of heritability (Hardon, 1976), results of single trials may mean little. Through repeated experiments with different populations and locations, a general picture of heritabilities can be built up. Some characters, such as yield of fruit, tend to be more sensitive to environmental fluctuations, and thus generally have lower heritabilities, than others, such as fruit composition.

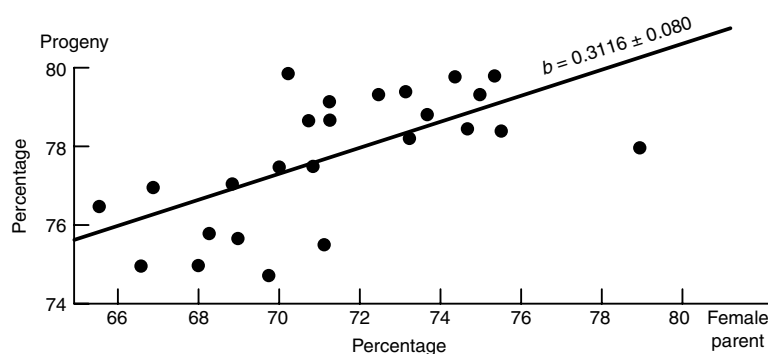


Fig. 5.7 Regression of progeny mean mesocarp/fruit on female parental values.

A point worth noting is that misidentification of quite small percentages of individual palms will have a large effect on estimates of genetic variances. Ericsson (1999) showed by simulation that a 2% error could reduce the apparent amount of additive variation by one-third, and increase the non-additive variation. Given the known errors in pedigrees already mentioned, this must be relevant to oil palm studies. Hardon (1976) pointed out that several assumptions are made in the theory of quantitative genetics that are not usually met in breeding trials (in particular, the requirement that parents be a random sample from the base population). This will introduce further, unknown bias into the results. These points should be remembered when looking at published work on heritabilities, as summarised in Sections 5.3.2–5.3.4.

5.2.6.3 Breeding values

The breeding value of a parent (also known as the additive breeding value or genotypic value) is the average value of all crosses from that parent; this is usually expressed as a difference from the overall mean for the trial or crossing programme. Once breeding values have been estimated, they may be used to predict the performance of crosses. The expected value of a cross is simply the mean of the breeding values of the parents, all expressed as deviations from the population mean, in the same units as the character measured. The use of breeding values is discussed in Section 5.4.2.4.

The terms general combining ability and specific combining ability (GCA and SCA) are also sometimes used. The GCA value of a parent is equal to half its breeding value. The SCA for two parents is the amount by which the cross between them deviates from expectation based on their GCA values. These terms may also be applied to populations; they then have approximately the same meaning as additive and non-additive variation (Section 5.2.6.2).

The simplest method of estimating additive breeding values is to use 'breeding triangles', in which sets of three parents are crossed in all combinations. The phenotypic value (X) for each cross for the character of interest is assumed to be the average of the genotypic or breeding values (BV) of its parents:

$$X = (BV_1 + BV_2)/2 \quad (5.6)$$

A triangle of crosses gives three such equations, and the breeding values can be calculated by simple algebra. The example given by van der Vossen (1974) is shown in Table 5.8. This method implicitly assumes completely additive inheritance, but non-additive variation is

Table 5.8 Observed values for kernel/fruit (K/F) and calculated breeding values for the parents

Parents	K/F	Calculated breeding values		
		4.3488	G145	2.381D
4.3488 × G145	9.4	7.0	11.8	–
4.3488 × 2.381D	10.0	7.0	–	13.0
G145 × 2.381D	12.4	–	11.8	13.0

From van der Vossen (1974).

clearly important for some characters (Section 5.3). Strictly, the following equation is the correct one:

$$X = (BV_1 + BV_2)/2 + SCA + \text{error} \quad (5.7)$$

When the same palm is included in more than one triangle, different BVs will often be obtained, owing to SCA effects or experimental error, or both. The mean of several BV estimates should be more reliable than a single value, but the accuracy with which the performance of a particular cross can be predicted will depend on the size of any SCA effect, which is not predictable.

A better method is to use the values from all crosses in a connected design (Section 5.2.2) and estimate breeding values by multivariate analysis. A worked example of this method was given by Breure and Verdooren (1995). The proportion of total variation between family means which is explained by such an analysis will be the proportion of additive variation to total genetic variation.

5.2.7 Selection at the immature stage

Given the long generation time for oil palm breeding (Section 5.2.3), the possibility of selection at the nursery stage has often been considered. Devuyst (1954) suggested that the palms which grew fastest in the nursery, measured in terms of height at 1 year old or on the basis of nursery leaf production, would also yield most in the field, and only those above average should be planted. However, Sparnaaij (1955) argued that any correlation was probably due to environmental rather than genetic effects, and presented data showing that, while leaf production of immature field palms was correlated with early yield (years 5–6 after planting), there was no relationship with yield from years 7–13. Less environmental variation might be expected in a polybag nursery than in a field nursery, but in a later study, although a positive correlation between nursery leaf area and early growth in the field was found, this also was thought not to have a strong genetic basis, because heritabilities of the nursery measurements were very low (Tan and Hardon, 1976).

Corley *et al.* (1973b) found significant genetic variation for some photosynthetic characteristics measured in the nursery, but later found no correlations with yield of the same crosses (unpubl.). More recently, Smith (1993a) suggested using nursery measurements of photosynthesis and stomatal opening as selection criteria. However, it appears that growth of immature palms is probably not limited by rate of photosynthesis (see Section 4.1.5.8), whereas yield of mature palms does depend on rate of photosynthesis, so correlations between photosynthesis or growth of young palms and yield at maturity are, perhaps, unlikely.

Kouame (1978) and Kouame and Noiret (1980) measured mitochondrial activity (mitochondria are the cellular organelles responsible for respiration), and found highly significant correlations with progeny yields. According to Le Guen *et al.* (1989), this method is in routine use, but P. Dunn (1982, unpubl.) found that environmental factors (fertiliser, water supply) had at least as great an influence on mitochondrial activity as did progeny or clonal differences. Thus, very careful standardisation of conditions is essential if this method is to be successful.

One area where nursery selection does play an important role is in breeding for resistance to *Fusarium* wilt. This is discussed in Section 12.1.6.2. Apart from disease screening, the best hope for early selection appears to lie in the use of molecular markers.

5.2.8 Molecular markers in oil palm breeding

Variation in yield components or vegetative characters results from differences in the genes, which carry instructions for the synthesis of enzymes (proteins). With molecular markers, either the proteins or the genes themselves (DNA) are studied. Very large amounts of genetic variation are easily identified, and these markers can be used for confirmation of pedigree or legitimacy, for assessing genetic diversity, or for 'marker-assisted' selection of individuals, or of parents to create a desired cross. Selection based on DNA will be more reliable than conventional selection based on phenotype, because the latter is affected by environment as well as genotype.

5.2.8.1 Types of marker

The first work on molecular markers was with proteins: some enzymes exist in more than one form (isoenzymes or isozymes), and these forms can be separated and their inheritance studied. Some work has been done with oil palm (Ghesquiere, 1984, 1985; Ataga and Fatokun, 1989b; Baudouin, 1992; Choong *et al.*, 1996), but protein markers are difficult to work with. The

enzymes present differ between tissues, and even within the same tissue may vary with physiological status of the plant, so it can be difficult to obtain comparable samples from different plants; also, there are relatively few enzymes for which the isozymes are easily separated and identified.

The most reliable markers are those based on DNA; these depend on the distinctive structure of the genetic material, and have largely replaced protein markers in genetic studies. DNA consists of two parallel strands, each a chain of millions of the four bases, adenine, guanine, cytosine and thymidine (A, G, C and T). Within a single strand, the sequence of these bases forms the genetic code, carrying instructions for the synthesis of proteins. Differences between individuals, both within a species and between species, all result from differences in the sequence of bases in DNA. The two parallel strands form a double helix, linked together by hydrogen bonds between complementary pairs of bases: A always pairs with T, and G always with C. Thus, one strand can be thought of as a sort of negative image of the other. The attraction between the corresponding sequences of bases is strong, and is the basis both of DNA replication during cell division, and of marker techniques. Marker methods depend on the attachment of a short fragment of DNA to a point on the longer chains where the base sequence is complementary to that of the fragment. A large proportion of the DNA of most plants, including oil palm, consists of repetitive sequences separating the genes. Many of these repetitive sequences have no known function, but their frequency makes them useful in marker studies. Castilho *et al.* (2000) studied repetitive DNA sequences in oil palm, using fluorescent labelling to locate the position of sequences on the chromosomes (Plate VIC).

The longest established DNA marker technique uses restriction fragment length polymorphisms (RFLPs). With this method, DNA is extracted from the plant and cut into fragments with a restriction enzyme. These enzymes cut the DNA chain wherever they find a particular sequence of bases; because the sequences differ between individuals, so will the points of cutting, and hence the size of the resulting fragments. The fragments are separated according to size by gel electrophoresis, and radioactive probes (short pieces of DNA) are then used to locate fragments with a sequence matching that of the probe. The pattern of DNA fragments identified by a probe gives a 'fingerprint' (Plate 5.5) which, if repeated with enough different probes, is unique for every genotype.

RFLPs give reliable and repeatable results, but have the disadvantage of being laborious and time consuming, because of the need to extract and purify the DNA,

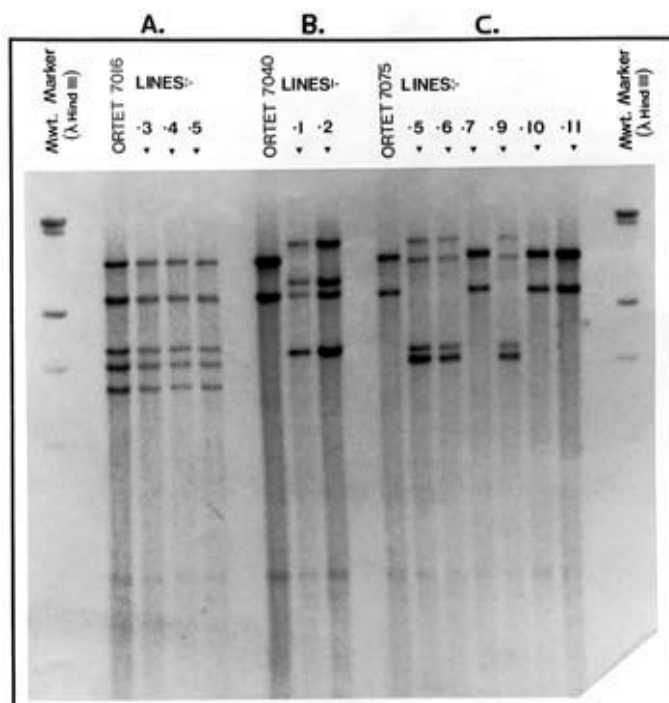


Plate 5.5 RFLP marker banding patterns for ortets, and for clonal lines supposedly derived from them. Each vertical track represents a single DNA sample. Clones derived from ortet 7016 are correct, but those from 7040 show a different pattern from the ortet, so cannot be derived from it. For 7075, some clonal lines are correct and others wrong. The tracks at each side are molecular weight markers. (From Mayes *et al.*, 1996.)

to digest it with the restriction enzyme, and to expose the photographic film used to detect the radioactive probes. The use of radioactivity may also impose limitations. Methods based on the polymerase chain reaction (PCR) are much simpler, and require only very small quantities of DNA. PCR makes use of an enzyme, DNA polymerase, which synthesises the complementary strand to a section of single-stranded DNA, starting from short sequences of bases known as primers, which match and 'anneal' to part of the single strand. Some methods use a pair of primers, which match sites separated by up to 1000 bases, to give more information. The chain reaction involves separating the resulting double strands, repeating the polymerase-catalysed synthesis, this time for both the original strand and the new strand, and separating the strands again; typically, this may be repeated up to 35 times, giving an amplification of the original DNA material of, potentially, up to 2^{35} . It is the primers which give the specificity, in the same way as the probe does for RFLPs; the primer anneals to regions of DNA with a sequence of bases matching that of the primer, and the polymerase activity and amplification are limited to DNA adjacent to these regions. The resulting amplified fragments will vary in size between individuals, either because of differences in primer annealing sites, or because the distance between primer pairs varies. As large amounts

of product can be generated, there is no need for a sensitive detection system using radioactivity; a simple fluorescent staining procedure is sufficient. Each different primer pair will result in the amplification of a different set of DNA fragments, so, again, a fingerprint can be built up by using several primers.

There are a variety of different PCR methods [rapid amplification of polymorphic DNA (RAPD), simple sequence repeats (SSRs) or microsatellites, aSSRs or anchored microsatellites, and an ever-increasing range of variants based on these methods]. Although much easier to use than RFLPs, some of these methods (particularly those which rely on arbitrary sequence primers such as RAPDs and aSSRs) do not always give reproducible results, and most methods will only detect quite large differences between individuals. In contrast, RFLPs can detect changes of a single base in the sequence, because of the specificity of the restriction enzyme. Amplified fragment length polymorphisms (AFLPs) use restriction enzymes together with PCR, and combine the precision of RFLPs with the simplicity of PCR. The method yields large quantities of data, but results may be difficult to interpret, and the technique is protected by patent. Microsatellites provide one of the best PCR marker systems, as they allow amplification of specific regions, are amenable to automation and are simple to score. However, identifying suitable primer pairs is time

consuming and expensive; Billotte *et al.* (2001) described the development of microsatellite markers for oil palm.

5.2.8.2 Fingerprinting

The unique fingerprints that DNA markers can provide for individuals have been used in oil palm breeding to check on the legitimacy of crosses (Mayes, 1995) and to confirm the identity of clones and ortets (Mayes *et al.*, 1996). Plate 5.5 shows a comparison of ortets with clones supposedly derived from them; clone 7040, and some lines of 7075, have different banding patterns from the ortets, indicating identification errors at some stage in the tissue culture process. Markers can also be used to investigate genetic diversity and relationships between breeding populations (Shah *et al.*, 1994; Mayes *et al.*, 2000; Moretzsohn *et al.*, 2002). The use of markers to compare different species of *Elaeis* is mentioned in Chapter 2. Figure 5.8 shows a range of different breeding parents grouped according to degree of similarity; the shorter the link between two palms, the more similar they are. An interesting point is that material from a recent selfing of SP540 is distinct from, but close to, AVROS material, as might be expected from the ancestry (see Section 5.1.1.3, and Fig. 5.2).

Kularatne *et al.* (2000) used AFLP markers, and Rajanaidu *et al.* (2000c) used RAPDs and RFLPs, to compare the different populations collected by MPOB (Section 5.1.7.2). In the study by Kularatne *et al.*, the Madagascar population was quite distinct from others, as was the Cameroon material in most of the analyses done. Tanzanian material clustered with Angola, Congo, Ghana and Nigeria, while Gambia, Senegal and Sierra Leone formed another group. Deli *dura* material was also included. It is not known where in Africa the Deli originated from, but there has been speculation that it might have come from Angola. The analyses undertaken by Kularatne *et al.* do not support this, the Deli material being quite distinct from all the African populations. In the study by Rajanaidu *et al.* (2000c), Madagascar was less distinct from other groups, and Deli was close to Nigeria, and not so distinct from Angola. The grouping in diversity trees such as Fig. 5.8 can depend on the method of statistical analysis, and on the number of markers used. Clearly, there are still discrepancies between different analyses, but these may be resolved as more markers are applied and more individuals from each population are studied.

5.2.8.3 Mapping and linkage studies

The DNA fragments identified with marker methods may be either parts of functional genes or non-functional

repetitive sequences. In either case, because they are carried on the chromosomes, they are inherited according to Mendel's laws, in exactly the same way as genes. If markers linked to useful traits (yield, oil/bunch, disease resistance) can be identified, then marker-assisted or marker-based selection becomes possible. Such selection can be done for characters that are not being expressed phenotypically; for example, immature palms could be screened for a yield marker, or disease resistance could be selected for in an area where the disease did not occur. The first step is to develop a linkage map. By screening a large population of sibs (at least 100 plants) for many different markers, pairs or groups of markers that are linked, and tend to be inherited together, can be identified. Such groups are expected to be on the same chromosome, and the closeness of the linkage, calculated statistically, shows the relative positions of the markers along the chromosome.

The first map published for oil palm, based on RFLPs, was published by Mayes *et al.* (1997); an updated version of this is shown in Fig. 5.9 (from Jack *et al.*, 1998). There were 24 linkage groups (reduced to 22 by Rance *et al.*, 2001); as *Elaeis* has only 16 chromosomes, further work should allow some of these groups to be combined. Group 13 included the shell-thickness gene, *sh*; marker 1282 was quite closely linked to *sh* (Plate 5.6), and in principle could be used to select fruit forms at the nursery stage. This would be useful to breeders, who would often like to plant the *pisiferas* from T × T crosses separately from the *duras* and *teneras*. In practice, the linkage was not quite close enough; there was about 10% 'crossing over', which means that only 90% of individuals would be fruit-typed correctly with the marker. Other genes mapped by the same research group were *virescens* (*vir* in group 11; see Section 5.3.3.3) and a gene for crown disease susceptibility (see Section 5.3.5 and Chapter 12).

An AFLP map with 20 linkage groups was published by Chua *et al.* (2001), and an AFLP and microsatellite map with 18 groups by Bilotte *et al.* (2001). The latter included an AFLP marker linked to the shell-thickness gene. Moretzsohn *et al.* (2000) identified two RAPD markers linked to the shell-thickness gene. These were not as close as the RFLP marker 1282 mentioned above, but with one marker to each side of the gene along the chromosome, reliable fruit-typing might be feasible.

Once a linkage map has been developed, it can be used to choose a set of markers that covers all chromosomes with reasonably even distribution. Other populations can then be screened for this subset of markers and studied for linkages with useful characters. Jack *et al.* (1998) and Rance *et al.* (2001) described such

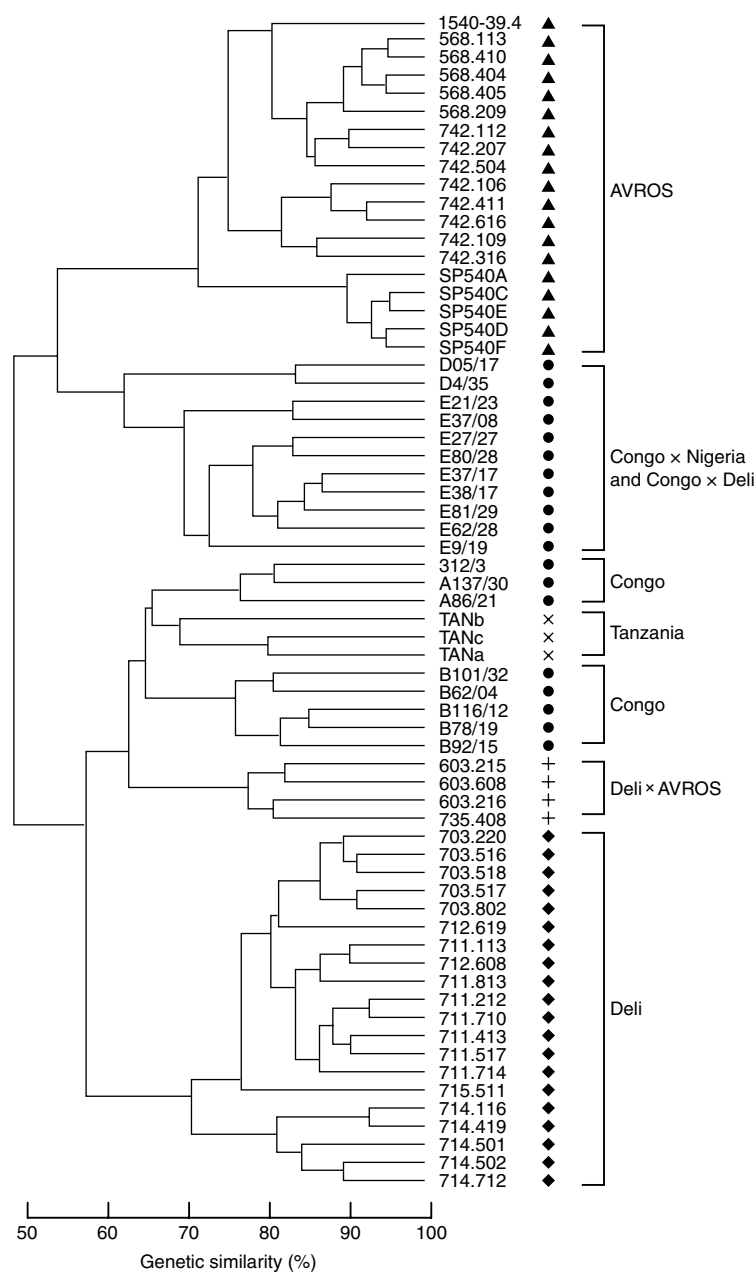


Fig. 5.8 Cluster analysis for oil palm breeding parents, based on 40 RFLP markers. Individual palm numbers are given, as well as a broad grouping of origins. (From Mayes *et al.*, 2000.)

a study with oil palm; RFLP markers were identified linked to FFB yield, oil/bunch and its components, and vegetative characters. Rajinder *et al.* (2001) identified markers linked to carotene content and oleic acid content of the oil. In principle, these linkages allow selection for yield at the nursery stage. Such linkages are likely to be specific to the population studied, so continuing work

is needed, using PCR-based markers, if this approach is to be useful to breeders, but the potential for marker-assisted selection in oil palm has been clearly demonstrated. Rance *et al.* (2001) and Rival *et al.* (2001) discussed the possibilities in some detail.

Koutou *et al.* (1992) claimed to have found isozyme markers linked to oil/mesocarp, but the paper included

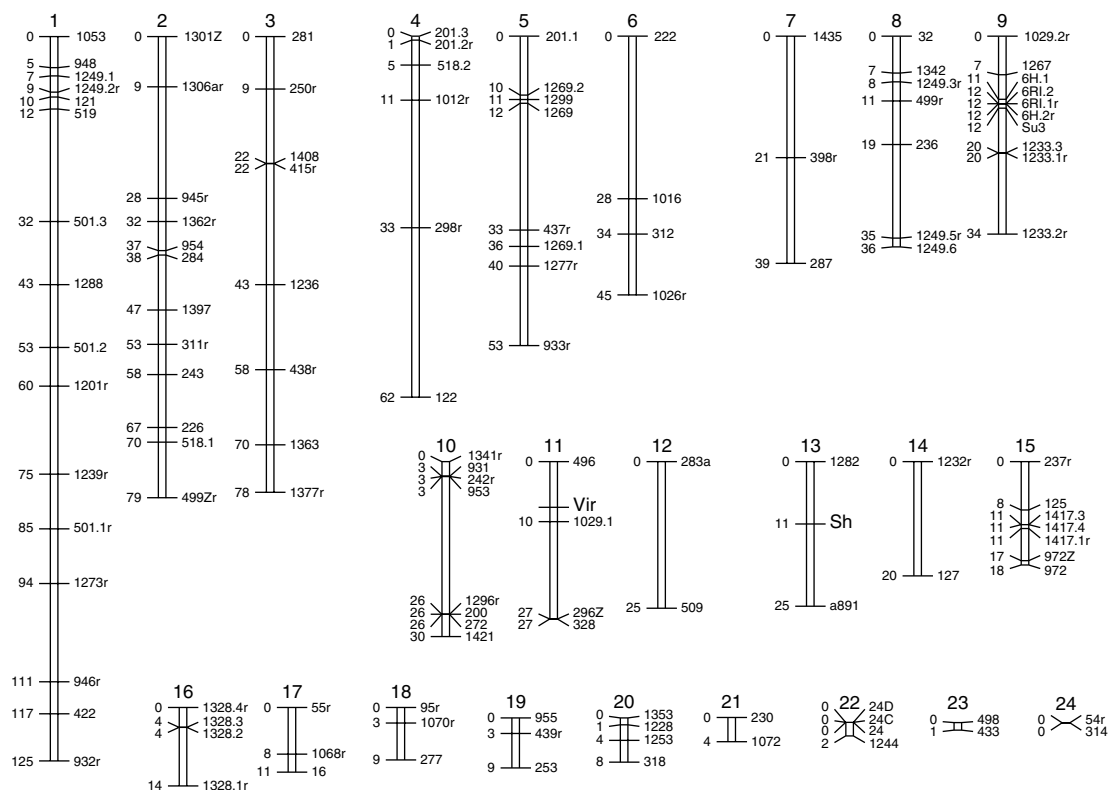


Fig. 5.9 RFLP genetic linkage map. The shell thickness gene is shown in linkage group 13, and the *virescens* gene in group 11. (From Jack *et al.*, 1998.)



Plate 5.6 RFLP marker SP1282, linked to shell thickness gene. Most *duras* carry the lower band, *pisiferas* the upper band and *teneras* both bands. The arrow indicates a *dura* where crossing over has taken place, so that the palm is heterozygous for the marker, although homozygous *sh* + for shell thickness. (From Mayes *et al.*, 1997.)

some clearly erroneous data, and according to Jacquemard *et al.* (1997) the method is not being used in practice.

5.3 VARIATION AND INHERITANCE

Variation is the raw material with which plant breeders have to work. The progress made in a breeding

programme depends both on the amount of variation present in the population before selection starts, and on the heritability of the characteristics selected for. The choice among selection criteria is discussed in Section 5.4. In this section, the ranges of variation found for various characteristics, and their heritabilities, are reviewed. The gradual loss of variation in successive generations of breeding programmes, and

hence the need to introduce new material, has already been mentioned in Section 5.1.6.

5.3.1 Sources of variation

A limited number of single genes with clear qualitative effects has been identified in the oil palm. The most important of these is the gene controlling shell thickness; this, and other genes affecting fruit form, are discussed in Section 5.3.3. One gene affecting vegetative development, the *idolatrix* gene, is also known (Section 5.3.4).

The majority of characters measured by oil palm breeders are polygenic (Section 5.2.6.1): yield of bunches, and its components bunch number and mean bunch weight, oil/bunch and its components, height, leaf area, and so on. In the following sections, the extent of variation for the more important characters is assessed, and what is known of their inheritance is summarised.

5.3.2 Bunch yield and its components

There is considerable variation in yield in unselected populations of oil palms (summarised by Hartley, 1988, p. 222 *et seq.*), but after several generations of selection, much of this variation may be lost, at least in narrowly based populations such as Deli *dura*. Thomas *et al.* (1969b) and Ooi *et al.* (1973) found very little additive variation in six different trials with Ulu Remis Deli *dura* material. Okwuagwu (1993) found little additive variation in the NIFOR Deli population (derived from Serdang Avenue palms; see Fig. 5.1), but when these were crossed with Deli *duras* from other programmes, variation was stated to be considerable. Hardon *et al.* (1987) found that variation was increased when Delis were out-crossed to African material. In Deli $\times$ AVROS progeny trials in PNG, Dumortier (2000) found that the range of oil + kernel yields for individual progenies was up to $\pm 30\%$ of the mean in some trials. Kushairi and Rajanaidu (2000) also reported a range of oil + kernel yields from Deli $\times$ AVROS progenies of $\pm 25\%$ of the mean (averaged over 15 years). Even in crosses between such narrowly based populations, therefore, there may still be considerable variation.

Mean bunch weight for individual palms varies with age, from only a few kilograms when first in bearing, to over 50 kg in old palms, depending on soil fertility and genotype. A typical well-grown mature field in Africa may have a mean bunch weight of 20 kg, while in very fertile soils in Malaysia or Indonesia mean bunch weights of 30–40 kg may be attained (Hartley, 1988). Bunch number and mean bunch weight are negatively correlated (Sparnaaij, 1969; Ooi *et al.*, 1973; van der

Vossen, 1974). As discussed in Chapter 4, this appears to be because yield is generally 'source limited'; that is, the supply of carbohydrates from photosynthesis is the limiting factor. Thus if, for example, bunch number is increased by selection, without any change in photosynthetic capacity, mean bunch weight must inevitably be reduced to compensate. Blaak (1965) argued that there was a ceiling yield determined by the environment, and that bunch weight and number were negatively correlated only in material where yield reached this ceiling; with lower yield potential, bunch number and weight varied independently. Support for this view came from the work of Okwuagwu (1989), who found no correlation between bunch number and bunch weight during the early years of production, when there was no effect of competition on yield (Section 5.4.4), but a negative correlation from the third year onwards (although this was only significant in one trial of the two studied). The logical extension of these observations is that these yield components are not in themselves very important; what matters is the amount of assimilates available for bunch production, and the resulting yield. Despite this, bunch number and weight have received much attention from oil palm breeders.

Yield and its components bunch number and bunch weight are polygenic characters. Heritabilities of bunch number and mean bunch weight are often quite high, but that for FFB yield is usually low (Table 5.9). This apparent anomaly is possible because of the negative correlation between bunch number and weight. Note that broad sense heritability (including non-additive variation) was higher in the Deli *dura* population than narrow sense heritability (Thomas *et al.*, 1969b). Blaak (1965) suggested that there was at least one major gene affecting bunch weight, which appeared to segregate to give distinct peaks in the bunch weight distribution for some crosses, but this has not been confirmed by others. Sparnaaij (1969) and van der Vossen (1974) found predominantly additive variation in bunch number and weight but, as Okwuagwu (1989) pointed out, their use of breeding triangles to calculate breeding values assumes that all variation is additive (see Section 5.2.6.3). Okwuagwu and West *et al.* (1977) used analysis of variance, and estimated that non-additive variation was significant for both yield components in the NIFOR programme.

In most studies, the heritability of bunch number is higher than that of bunch weight. This implies that bunch number is under stronger genetic control, with bunch weight being the component that is adjusted to match supply and demand for assimilates. That is surprising, given that bunch weight is clearly more stable from season to season (see Section 4.4).

Table 5.9 Heritabilities of bunch yield and its components, with standard errors

Material, location	Trial	h^2	FFB yield	Bunch no	Bunch wt	Ref.
D × T, Nigeria		h_n^2	0.0–0.36	–	0.41	1
Deli dura, Malaysia	1	h_n^2	0.19 ± 0.19	0.54 ± 0.20	0.19 ± 0.19	2
	2	h_n^2	0.40 ± 0.21	0.39 ± 0.32	0.37 ± 0.25	
	3	h_n^2	0.48 ± 0.26	0.54 ± 0.57	-0.36 ± 1.24	
	4	h_n^2	0.32 ± 0.27	0.90 ± 0.21	0.31 ± 0.25	
	5	h_n^2	0.07 ± 0.25	0.22 ± 0.44	-0.12 ± 0.32	
Deli dura, Malaysia	1	h_n^2	0.30 ± 0.17	0.51 ± 0.23	0.29 ± 0.17	3
	2	h_n^2	0.29 ± 0.17	0.63 ± 0.26	0.46 ± 0.20	
	3	h_n^2	-0.20 ± 0.24	-0.57 ± 0.32	-0.03 ± 0.23	
	3	h_b^2	0.57 ± 0.41	1.06 ± 0.64	0.40 ± 0.33	
	4	h_n^2	0.22 ± 0.22	-0.24 ± 0.16	-0.20 ± 0.10	
	4	h_b^2	0.04 ± 0.12	0.93 ± 0.54	0.87 ± 0.40	
Deli dura, Malaysia		h_n^2	0	0.18	0.25	4
		h_b^2	0.88	0.52	0.69	
D × P, Malaysia		h_n^2	0.06	0.70	0.49	5
		h_b^2	0.33	0.70	0.74	
T × T, Ghana		h_n^2	0.09	0.51 ± 0.21	0.21 ± 0.13	6
D × T or D × P, Malaysia		h_n^2	0.06–0.13	–	–	7
		h_b^2	0.09–0.22	–	–	
D × P, Malaysia	1	h_n^2	-0.25 ± 0.40	0.22 ± 0.44	0.90 ± 0.50	8
	3	h_n^2	-0.19 ± 0.36	-0.39 ± 0.22	0.06 ± 0.29	
	4	h_n^2	0.19 ± 0.19	0.63 ± 0.60	0.12 ± 0.06	
D × D, Malaysia	2	h_n^2	0.07 ± 0.32	1.46 ± 0.24	0.53 ± 0.33	
Fertile pisifera, Malaysia		h_n^2	0.16	0.31	–0.08	9
D × P, Malaysia		h_n^2	0.22	0.64	–	10
Clones, Ivory Coast		h_b^2	0.10–0.74	0.25–0.85	0.01–0.91	11
Clones, Ivory Coast		h_b^2	0.28–0.43	0.55–0.70	0.42–0.65	12

h_n^2 : narrow sense heritability; h_b^2 : broad sense heritability. Theoretically, h^2 must have values between 0 and 1, but values outside this range may be found by chance.

References: 1: Blaak (1965); 2: Hardon and Thomas (1968); 3: Thomas *et al.* (1969b); 4: Ooi *et al.* (1973); 5: Ooi (1975b);

6: van der Vossen (1974); 7: Hardon *et al.* (1972); 8: Ahiekpor and Yap (1982); 9: Chin (1988); 10: Soh and Chow (1993);

11: Baudouin and Durand-Gasselin (1991) (range of values from ten trials); 12: Cochard *et al.* (1999) (range of values from three trials).

Despite recognising that bunch number and weight are negatively correlated, Sparnaaij (1969) and Gascon and de Berchoux (1964) argued that, if number and weight are independently and additively inherited, yield would be increased by crossing high bunch number (B no.) palms with high bunch weight (B wt) palms. This was based on simple arithmetic, assuming that the cross will have bunch number and weight equal to the means of the parental values:

	B no. (per year)	Mean B wt (kg)	Yield (kg/year)
Palm A:	16	10	160
Palm B:	8	20	160
Cross A × B:	12	15	180

This ignores the probability that yield is source limited (see above and Chapter 4), but this point was recognised by BOS and Sparnaaij (1993). Examples of crosses which appear to fit the hypothesis can be found, but the explanation is more likely to be that, when unrelated populations are crossed, hybrid vigour results in an increase in source activity and thus in yield potential, whether or not the populations differ in bunch number and weight.

Sitepu *et al.* (2002) showed that there was a large amount of variation within families for bunch weight, and also that trends of weight with age varied. They suggested that the ideal palm would have high early bunch weight, and relatively low bunch number to minimise pollination problems (Section 4.5.2), but that bunch weight should not exceed about 25 kg in older palms. Heavier bunches are difficult to handle, whether by hand or mechanically, difficult to sterilise in the

mill, and may also have lower oil content than lighter bunches (Section 4.5.2).

Blaak (1972) measured precocity, as the percentage of palms in a progeny which carried female inflorescences 36 months after germination. He showed that this was quite repeatable in different trials with the same crosses, and he calculated breeding values and a broad sense heritability of 0.68. In many trials, precocious progenies may be missed, as yield recording is often started at a predetermined age, rather than when bunches start to be available.

5.3.3 Inheritance of fruit characters

The shell thickness gene has major effects on bunch composition, with *teneras* typically having about 30% more mesocarp and hence 30% greater oil content in bunches than *duras*. Superimposed on the effects of this major gene, there is also continuous variation in shell thickness within the fruit types, presumably controlled by minor genes. This component of bunch quality is discussed first, before considering other components which are under polygenic control. Other fruit characters controlled by single genes are mentioned at the end of the section.

5.3.3.1 Variation in shell thickness

Fruit forms: As described in Section 5.1.5, Beirnaert and Vanderweyen (1941) first recognised that large differences in shell thickness are controlled by a single gene (Plate IIA). This gene has two codominant alleles, *sh+* and *sh-*; thick-shelled, *dura* palms are homozygous for *sh+*, while palms homozygous for *sh-* are shell-less *pisiferas*. The heterozygote, *sh+/sh-*, is intermediate, with a thin shell. Some authors describe the *sh+* allele as dominant. This is not correct, as the heterozygote is intermediate between the two homozygotes; if *sh+* were dominant, *sh+/sh+* and *sh+/sh-* would have the same phenotype.

When pollen grains and ovules are formed by meiosis, each receives one allele of every gene, at random. For shell thickness, all *pisifera* pollen grains will be *sh-*, while all *dura* ovules are *sh+*, so a *D* × *P* cross will consist solely of *teneras* (*sh+/sh-*). It must be noted that the shell is maternal tissue, so all seeds from *dura* mother palms will have thick shells, whatever the fruit form of the pollen parent. This is often misunderstood; one published field manual recommends that planters should reject thick-shelled ‘*dura*-type’ seeds as abnormal (Rankine and Fairhurst, 1998a).

Table 5.10 Segregation of fruit forms in a *T* × *T* cross

		Pollen grains	
		<i>sh+</i>	<i>sh-</i>
Ovules	<i>sh+</i>	<i>sh+/sh+</i>	<i>sh+/sh-</i>
	<i>sh-</i>	<i>sh+/sh-</i>	<i>sh-/sh-</i>

When a *T* × *T* cross is made, pollen grains and ovules may carry either allele, at random. As Table 5.10 shows, there are four possible combinations in the fertilised ovule, but it does not matter which parent contributes which allele, so two of these are identical, *sh+/sh-*. Thus, the fruit forms from a *T* × *T* cross are found in the ratio 1 *dura*:2 *tenera*:1 *pisifera*. From a *D* × *T* cross, the expected ratio is 1 *dura*:1 *tenera*, and from *T* × *P*, 1 *tenera*:1 *pisifera*. *D* × *D* and *P* × *P* are the only crosses which breed true.

In the original Congo *tenera* selfings and *T* × *T* crosses some divergences from the 1:2:1 ratio were found (Beirnaert and Vanderweyen, 1941). While *tenera* progeny remained nearly constant at 50%, a few *tenera* mother palms gave as much as 35% or as little as 15% *dura*, with a correspondingly low or high proportion of *pisifera*. Such cases can result from contamination of *tenera* pollen with small quantities of either *dura* or *pisifera* pollen. For example:

<i>Tenera</i> × <i>tenera</i>	15 D	30 T	15 P
(legitimate, 60%):			
<i>Tenera</i> × <i>dura</i>	20 D	20 T	0 P
(contaminant, 40%):			
Total (100%):	35 D	50 T	15 P

However, detailed examination in Congo showed quite consistent behaviour, which would not be expected with contamination. *Teneras* were classified as type I, giving normal segregation, type II, giving an excess of *duras*, and type III, giving an excess of *pisiferas*. A few examples from the work of Beirnaert and Vanderweyen are given in Table 5.11, showing that types II and III gave intermediate segregations when crossed with type I. These departures from the expected segregation have not been recorded on a large scale elsewhere, and no fully satisfactory explanation has been provided, although de Poerck (1942) suggested a hypothesis based on the presence of a series of alleles modifying the proportions of the three fruit forms in *tenera* × *tenera* progeny.

Table 5.11 Segregation from different types of *tenera* in Congo.
See text for an explanation of 'types'

Type of <i>tenera</i>	Segregation of fruit forms (%)			No. of palms
	<i>Dura</i>	<i>Tenera</i>	<i>Pisifera</i>	
Type II selfs and crosses	32.6	51.3	16.1	353
Type III selfs and crosses	14.8	49.2	36.0	390
Type II × normal (type I)	28.8	50.9	20.3	645
Type III × normal (type I)	19.5	51.4	29.1	492
Type II × Type III	74.2		25.8	275

From Beirnaert and Vanderweyen (1941).

Variation within fruit forms: Within the *dura* and *tenera* fruit forms, there is polygenic variation in shell thickness, superimposed on the major difference due to the *sh* gene (Plate IID). In Chapter 2 the *dura* fruit form was described as having shell 2–8 mm thick (though occasionally less), mesocarp content 35–55% (but sometimes, as in the Deli palm, up to 65%) and no fibre ring. The *tenera* has shell 0.5–4 mm thick, 60–96% mesocarp (but occasionally as low as 55%) and a fibre ring. Initially, shell thickness was taken as the main classifying measurement: Beirnaert and Vanderweyen (1941) defined the *tenera* as fruit with a shell thickness of 0.5–2 mm. The clear segregation ratios in the classic work of these authors were obtained because they used *tenera* with low shell thickness, thus ensuring that only genuine *tenera* were being used and that the progeny would not be hard to classify. Later, it was realised that *dura* of shell thickness less than 3 mm, and *tenera* of shell thickness over 3 mm, could be found, and the presence or absence of a fibre ring gradually came to be recognised as the ultimate criterion.

Dura* and *tenera* shell thickness:** *Duras* are selected for seed production on the assumption that fruit and bunch characters of *dura* and *tenera* are highly correlated, but Sparnaaij (1969) and van der Vossen (1974) have questioned whether this assumption is valid for mesocarp/fruit and shell/fruit. Gascon and de Berchoux (1963) found a high correlation for mesocarp/fruit between *tenera* and *dura* sibs ($r = 0.87^{}$), but a lower value ($r = 0.56^{***}$) was obtained by Meunier *et al.* (1970), and van der Vossen (1974) reported a value of $r = 0.40^{***}$ for 104 D × T crosses from NIFOR annual reports. More recently, Okwuagwu (1988) summarised results of several studies in the NIFOR breeding programme: nine significant parent–offspring regressions for shell/fruit were found when the fruit forms were the same (*dura* with

dura parent, or *tenera* with *tenera* parent), but five regressions between parents and offspring of different fruit forms were all non-significant (Table 5.12).

Sparnaaij (1969) suggested that fruit composition in the *tenera* is determined not by a single factor, shell thickness, as is the case for the *dura*, but by two factors, the 'potential shell thickness', controlled by the same genes as actual shell thickness in the *dura*, and the degree of lignification of the potential shell region. In the *tenera* the potential shell thickness is represented by the actual shell plus the unlignified mantle of fibres around the shell. *Dura* parents have been selected on the basis of the shell thickness factor, whereas *tenera* parents are selected primarily because of their low degree of lignification. This latter factor is operative only in the *tenera*, causing the independent variation in observed shell thickness. Sparnaaij also indicated that kernel size was important.

Following up Sparnaaij's ideas, van der Vossen (1974) showed, in a study of *dura* and *tenera* sibs in 25 crosses, that, although *tenera* shell/fruit was not significantly correlated with that for the *duras*, a very high correlation existed ($r = 0.94^{***}$) between *dura* shell/fruit and *tenera* (shell + fibre mantle)/fruit. The correlation for mesocarp/fruit was low ($r = 0.45^*$), but *dura* mesocarp/fruit was highly correlated with mesocarp outside the fibre ring in *teneras* ($r = 0.85^{***}$). These results support Sparnaaij's hypothesis.

Kernel size varies considerably (Plate IID). A change in kernel size, if the shell thickness (in mm) remains the same, will have a greater relative effect on shell/fruit in *tenera* palms (in which the percentage kernel is of the same order of magnitude as the percentage shell) than in *duras* (see also Table 5.13). Van der Vossen (1974) concluded that where the kernel size of the parents differs, this leads to lower kernel/fruit, and hence also lower shell/fruit, in the *tenera* offspring. He did not explain



Plate 5.7 The wide variety of size and shape of nuts from African fruit.

Table 5.12 Heritability of fruit components, estimated by parent–offspring regression, from various studies in the NIFOR breeding programme

Comparison parent	Offspring	Type of cross	No. of crosses	Heritability (h_n^2)	
				WM/F	S/F
<i>Tenera</i> mid-parent	<i>Tenera</i>	T × T	72	0.84***	1.03***
<i>Tenera</i> parent	<i>Tenera</i>	D × T	86	0.67***	0.96***
<i>Tenera</i> parent	<i>Tenera</i>	Deli × T	96	0.35***	0.30**
<i>Tenera</i> parent	<i>Tenera</i>	D × T	31	0.88***	0.99***
<i>Dura</i> parent	<i>Dura</i>	D × T	30	1.13***	0.98***
<i>Dura</i> mid-parent	<i>Dura</i>	D × D	14	–	1.92***
Deli <i>dura</i> parent	<i>Tenera</i>	Deli × T	41	0.12 ns	0.05 ns
<i>Dura</i> parent	<i>Tenera</i>	D × T	37	0.32 ns	0.19 ns
<i>Tenera</i> mid-parent	<i>Tenera</i>	T × T	26	–	0.98***
<i>Tenera</i> mid-parent	<i>Dura</i>	T × T	26	–	0.19 ns
<i>Dura</i> parent	<i>Dura</i>	D × T	29	–	1.92***
<i>Tenera</i> parent	<i>Tenera</i>	D × T	29	–	0.68**
<i>Dura</i> parent	<i>Tenera</i>	D × T	29	–	0.31 ns
<i>Tenera</i> parent	<i>Dura</i>	D × T	29	–	0.58 ns

Data from Okwuagwu (1988), quoting van der Vossen (1974), and NIFOR reports.

h_n^2 : narrow sense heritability; WM: wet mesocarp; F: fruit; S: shell.

Significance of regression indicated by asterisks: *** $p < 0.001$, ** $p < 0.01$; ns: not significant.

how this came about, but it would appear to indicate linkage between genes for kernel size and the shell-thickness gene. Okwuagwu (1988) postulated the existence of ‘kernel-inhibiting’ and ‘shell-inhibiting’ factors transmitted by the *tenera* or *pisifera* parent to its *tenera* offspring. Where the kernel inhibiting factor is absent, *teneras* will have kernels as large as their *dura* sibs. These factors were supposed to be additively inherited, implying polygenic control, but were also assumed to be

closely linked both to each other and to the shell thickness gene. Okwuagwu and Okolo (1992, 1994) suggested that the kernel-inhibiting factor was closely linked to the shell-less allele of the shell thickness gene, and also ‘mainly inherited maternally’. This appears to be a contradiction, but it should be noted that endosperm (kernel) in most plants is triploid, receiving one set of chromosomes from the male parent and two from the female. Additive effects could therefore result in the

Table 5.13 Estimation of shell thickness in crosses from fertile and sterile *pisiferas*.

Nuts are assumed to be spherical; kernel, shell and mesocarp are assumed to have the same density, so that weights and volumes are equivalent

<i>Pisifera</i>	F wt (g)	K/F (%)	S/F (%)	Weight (g)			Radius (mm)		
				K	S	K + S	K	K + S	Difference = S (mm)
Fertile	12.68	12.2	14.5	1.55	1.84	3.39	3.6	4.65	1.0
Sterile	11.48	6.8	9.7	0.78	1.11	1.89	2.85	3.85	1.0

Based on data from Chin (1988).

F: fruit; K: kernel; S: shell.

female having more influence on the endosperm than the male, and an appearance of maternal inheritance.

The view that *teneras* have inherently lower kernel/fruit than *duras* seems to derive from the NIFOR programme (Sparnaaij, 1969; van der Vossen, 1974). Okwuagwu (1988) described a family in which the two were equal as 'unusual', and presented data from 43 families in which the mean *tenera* kernel/fruit was only 85% of the *dura* mean. However, Beirnaert and Vanderweyen (1941), with nearly 7000 *teneras* and over 3000 *duras*, found that the average kernel percentage to fruit was actually slightly higher in the *teneras*; Corley and Lee (1992) found very similar mean kernel/bunch ratios in *dura* and *tenera* sibs, in six trials with a total of 65 families.

The problem of the poor correlation between *dura* and *tenera* sibs for fruit characters is undoubtedly a real one, although it seems only to have been noticed in the NIFOR programme. The simplest explanation appears to be that there is polygenic variation in the degree of lignification of the 'potential shell' region in *teneras*, which is not expressed in *duras* where lignification is complete. Attempts to explain the situation in terms of kernel size have resulted in complex genetic models, but do not seem to have improved predictive value. Measurement of actual shell thickness, in millimeters, rather than expressing it as a percentage of total fruit weight, may resolve some of the discrepancies (see below). Meanwhile, in practical terms, the consequence of the poor correlation is that *dura* seed parents will be best evaluated for fruit characters by progeny testing, or by studying their *tenera* sibs if available.

Shell thickness and sterile pisiferas: Although most *pisiferas* are female sterile, fertile forms can be found. Wonkyi-Appiah (1987) studied the inheritance of fertility, and concluded that it may be controlled by a single gene, closely linked to the shell-thickness gene. Occasional crossing over would lead to the observed occurrence of female sterile *duras* and *teneras*.

Work at NIFOR has been interpreted as indicating that fertile *pisiferas*, when used to produce D × P crosses, give *teneras* with thicker shells than sterile *pisiferas*, and most breeding programmes have concentrated on sterile *pisiferas* as a result. The original argument for this (Sparnaaij *et al.*, 1963a) appears to have been based on the observation that fruit set was highest in *duras* and lowest in *pisiferas* (often nil in sterile *pisiferas*); thus, it was suggested that there was an association between shell thickness and fertility. Extrapolation from this comparison of fruit forms to variation within the *tenera* fruit form does not appear justified, and the main evidence for the hypothesis at that time came from the presence of more fertile *pisiferas* in T × T crosses from thick-shelled *teneras* (36% fertile) than from thin-shelled (23%) (Menendez and Blaak, 1964).

More recently, Chin (1988) compared D × P progenies from unrelated sterile and fertile *pisiferas*, and found much higher S/F and K/F, and lower WM/F, in the progenies from fertile *pisiferas*. This appears to support the hypothesis, but confusion arises from the use of the term 'shell thickness' to describe shell/fruit percentage. Table 5.13 shows that actual shell thickness, in millimeters, was probably much the same for both groups of *teneras*; the difference in S/F may just be a consequence of a difference in kernel size. Apart from this point, Rosenquist (1990) and Nelson (1993) pointed out that the sterile and fertile *pisiferas* were not related, so the association of S/F with fertility could have been fortuitous anyway. In a comparison of D × P progenies from fertile and sterile *pisiferas* from the same families (all Dumpy-AVROS; see Fig. 5.2), Nelson (1993) found that differences in shell/fruit, kernel/fruit and mesocarp/fruit were negligible (Table 5.14). These results indicate that the exclusion of fertile *pisiferas* from seed production programmes in the past may not have been justified.

Table 5.14 Fruit components in crosses from fertile and sterile *pisiferas*

Family	<i>Pisifera</i>	No. of		Mean actual values			Breeding values		
		<i>Pisifera</i>	crosses	WM/F	K/F	S/F	WM/F	K/F	S/F
DM770	Fertile	1	4	80.0	5.2	14.9	80.6	5.0	14.4
	Sterile	2	7	79.8	5.4	15.0	80.0	5.2	14.8
DM771	Fertile	1	4	79.0	5.8	15.2	78.7	5.8	15.4
	Sterile	1	4	78.6	5.7	15.7	78.3	5.7	15.9
DM773	Fertile	2	7	78.1	5.6	16.4	78.2	5.3	16.5
	Sterile	1	4	79.2	5.4	15.4	79.6	5.3	15.1
DM774	Fertile	1	4	78.5	5.8	15.7	78.4	5.8	15.8
	Sterile	2	7	80.3	5.1	14.7	80.8	4.8	14.4
Mean	Fertile	5	19	78.9	5.6	15.6	79.0	5.5	15.5
	Sterile	6	22	79.4	5.4	15.2	79.7	5.3	15.0

Data from Dami Oil Palm Research Station, Report on Research, 1977–1988.

Pisiferas of Dumpy–AVROS origin (50% Dumpy, 25% or 50% AVROS). From each family, two or three *pisiferas* were selected, including both fertile and sterile, and crossed with several Deli *duras*.

wm: wet mesocarp; F: fruit; K: kernel; S: shell.

5.3.3.2 Oil and kernel to bunch and their components

Oil/bunch depends on fruit/bunch, mesocarp/fruit and oil/mesocarp. The major effect of the shell-thickness gene on WM/F has already been discussed, but apart from this there is quantitative variation in all the components. Results of some heritability studies are summarised in Table 5.15.

The SIRIM standard for commercial seed production in Malaysia specifies that *dura* parents must have at least 55% mesocarp/fruit, 70% oil/dry mesocarp and 16% oil/bunch, based on at least three bunches analysed. However, it is important to bear in mind, when comparing bunch analysis data between one station and another, the range of different methods of bunch analysis, and the fact that some methods may introduce appreciable bias, as discussed in Section 5.2.4.2. Thus, it may be unrealistic to apply absolute standards for bunch components, rather than looking at relative differences within programmes. It should also be remembered that the pollinating weevil, *Elaeidobius kamerunicus*, was introduced in the Far East in 1982. Bunch components before and after that date were compared by Chan *et al.* (1988). They found higher fruit/bunch, oil/bunch and kernel/bunch, and lower mesocarp/fruit after the introduction, but heritabilities of bunch components were largely unchanged.

Fruit to bunch: The usual range for F/B is between 60 and 65%, but ratios below 60% are not uncommon, while progenies with F/B of over 70% are sometimes found. Both narrow and broad sense heritabilities for

this component tend to be quite low, and there is no doubt that the efficiency of pollination, an environmental factor, plays a significant part in determining fruit to bunch.

There appears to be a tendency for *duras* to have higher F/B than *teneras*. Gascon and de Berchoux (1963) found a significant correlation at La Mé in the Ivory coast between the F/B ratios of *duras* and *teneras* in the same progenies. Although *dura* palms had a higher F/B than the *teneras* in the same progeny, the difference between the two values diminished as the F/B ratio rose; while a *dura* F/B ratio of 50% corresponded to a *tenera* F/B of 43%, at the higher end of the range the correspondence was *dura* 75% and *tenera* 71%.

Mean fruit weight: This appears to have a high heritability; Meunier *et al.* (1970) found a value of 1.0, and variation is considerable, as shown by the data from the MPOB collections (Table 5.5). Hartley (1988) considered that the importance of fruit weight had been overestimated, but some studies have shown higher oil content in bunches with large fruits. Rajanaidu and Jalani (1994c) compared extremes (fruit weights of 3.7 g and 26.4 g), and found higher mesocarp/fruit, oil/mesocarp and oil/bunch with heavier fruits, but lower kernel/bunch. They argued that in small *tenera* fruits the fibre ring around the shell made up a larger proportion of the mesocarp, so that oil content was inevitably lower. Sharma and Tan (1997) compared more reasonable average fruit weights of 7.1 and 13.4 g. The bunches with heavier fruits had higher mesocarp/fruit, slightly higher oil/mesocarp and higher oil/bunch, but slightly lower fruit/bunch and lower kernel/bunch. No indication

Table 5.15 Heritabilities of bunch components with standard errors

Location	Material	h^2	F/B	M/F	O/M	K/F	O/B	Ref.
Ivory Coast	<i>Tenera</i>	h_n^2	-0.02 ± 0.18	0.52 ± 0.18	0.04 ± 0.12	0.65 ± 0.22	–	1
	<i>Dura</i>	h_n^2	0.01 ± 0.15	0.56 ± 0.17	0.07 ± 0.13	0.29 ± 0.28	–	
Ghana (T × T)	<i>Tenera</i>	h_n^2	0.55 ± 0.27	0.96 ± 0.18	0.25	0.66 ± 0.25	–	2
Ghana (D × T)	<i>Tenera</i>	h_n^2	0.18 ± 0.16	0.80 ± 0.23	0.23	0.60 ± 0.19	–	
Ghana	<i>Tenera</i>	h_b^2	0.17 ± 0.06	0.90 ± 0.02	0.46 ± 0.10	0.82 ± 0.04	–	3
Malaysia	<i>Deli dura</i>	h_n^2	0.07	0	0.48	0.07	0.18	
	<i>Tenera</i>	h_n^2	0.12	0.47	0.24	0.39	0.11	4
Malaysia		h_b^2	0.20 ± 0.07	0.79 ± 0.04	0.43 ± 0.08	0.60 ± 0.02	0.41 ± 0.08	
Nigeria	<i>Tenera</i>	h_n^2	0.62 ± 0.10	0.77 ± 0.13	–	0.67 ± 0.13	–	5
	<i>Tenera</i>	h_n^2	0.39 ± 0.10	0.84 ± 0.06	–	0.69 ± 0.08	–	
	<i>Tenera</i>	h_n^2	0.30 ± 0.08	0.67 ± 0.08	–	0.72 ± 0.07	–	
	<i>Tenera</i>	h_n^2	0.02 ± 0.06	0.35 ± 0.07	–	0.44 ± 0.04	–	
Malaysia	<i>Tenera</i>	h_n^2	0.01 ± 0.43	0.60 ± 0.50	0.20 ± 0.20	–	0.73 ± 0.69	6
	<i>Dura</i>	h_n^2	0.42 ± 0.40	0.85 ± 0.54	0.34 ± 0.05	–	0.67 ± 0.40	
	<i>Tenera</i>	h_n^2	0.08 ± 0.19	0.39 ± 0.39	-0.10 ± 0.09	–	0.09 ± 0.28	
	<i>Tenera</i>	h_n^2	0.20 ± 0.50	0.25 ± 0.24	0.12 ± 0.07	–	0.67 ± 0.26	
Ivory Coast	Clones	h_b^2	0.27–0.49	0.55–0.71	0.14–0.77	–	0.21–0.55	7
	Clones	h_b^2	0.18 ± 0.71	0.66	0.94 ± 0.54	–	0.49 ± 0.50	
PNG	<i>Tenera</i>	h_n^2	ns	0.40	0.17	0.74	0.49	8
Malaysia	<i>Tenera</i>	h_n^2	–	0.07	–	0.22	–	9
Ivory Coast	Clones	h_b^2	0.0–0.39	0.59–0.69	0.03–0.39	–	0.14–0.32	10
Malaysia	<i>Pisifera</i>	h_n^2	0.16	0.77	0.38	0.77	–	11
PNG	<i>Dura</i>	h_n^2	0.31	0.28	0.61	–	0.40	12

h_n^2 : narrow sense heritability; h_b^2 : broad sense heritability. Theoretically, h^2 must have values between 0 and 1, but values outside this range may be found by chance.

For abbreviations, see Table 15.1.

References: 1: Meunier *et al.* (1970); 2: van der Vossen (1974); 3: Ooi (1975a, 1975b); 4: Hardon (1976); 5: West *et al.* (1977); 6: Ahiekpor and Yap (1982); 7: Baudouin and Durand-Gasselien (1991) (first row is range of values from four trials); 8: Breure and Bos (1992); 9: Soh and Chow (1993); 10: Cochard *et al.* (1999) (range of values from three trials); 11: Chin (1988); 12: Dumortier (2000).

of the statistical significance of the differences was given. The economic yield (oil + 60% of kernel; see Section 5.4.1.2) was identical for large and small fruits, supporting Hartley's contention that fruit weight is not very important.

Mesocarp to fruit: There is considerable variation in this component among *teneras*, as discussed above (Section 5.3.3.1, *Variation within fruit forms*). Table 5.15 shows that, with the exception of one study in the *Deli dura* (Ooi, 1975a), narrow sense heritabilities are generally high, indicating that much of the variation is additively inherited. However, as discussed above (Section 5.3.3.1, *Dura and tenera shell thickness*), selecting *dura* seed parents with high M/F may not always give *teneras* with high M/F.

Oil to mesocarp: In the early days of oil palm selection and breeding little attention was paid to this component, in the mistaken belief that it approximated to 50% and was not very variable; when measurements were made,

the rather imprecise indirect method was often used (see Section 5.2.4.2, *Oil extraction*). O/WM is now measured routinely in breeding trials, but there are practical difficulties in its assessment.

- Oil content changes considerably during the ripening period. The bunch must be harvested fully ripe, and only ripe fruit must be used in the estimation of O/WM.
- The oil content of the fruit of young palms is always low; the mature level may not be reached until the fourth or fifth year of bearing, although Corley and Gray (1976b) found high oil/bunch ratios in palms aged 40 months.
- There are seasonal variations in oil percentages, fruit in the peak production months tending to have a higher oil content than fruit harvested at other times.
- Inner fruit tend to have lower oil/mesocarp than outer fruit (Rajanaidu and Jalani, 1994c).

In most published studies, it is not clear to what extent these variables have been accounted for, but it appears that O/WM may vary between palms from about 40% to just over 60%. Table 5.15 shows that heritability estimates are quite variable; there is a tendency towards higher broad sense than narrow sense heritabilities, indicating that non-additive variation may be important for this component.

Oil to bunch: Heritability of O/B has only been estimated in a few studies (Table 5.15); it appears that it is usually lower than that for WM/F, but as high as or higher than that for F/B. There is considerable variation in O/B, both between families and among individual palms. In Congo, in the Binga programme of over 700 crosses, Dumortier *et al.* (1992) found family mean O/B for *teneras* ranging from 14.2 to 26.8%. In a study of 715 individual *teneras* in a breeding trial in Malaysia, Rajanaidu *et al.* (1998b) found O/B ranging from as low as 4.2% to 38.2%. *Duras* typically have about 25% less oil to bunch than *teneras*; Corley and Lee (1992) found an average of 22.9% O/B for *teneras* in 65 families and 17.2% for their *dura* sibs. In the Binga programme, family mean *dura* O/B ranged from 9.2 to 22.5% (Dumortier *et al.*, 1992); Lee (1999) quoted individual Deli *duras* with O/B up to 28%.

Kernel to fruit: Variation in kernel size has already been discussed (Section 5.3.1.1, *Dura and tenera shell thickness*). Rajanaidu *et al.* (2000b) identified individual palms among the Nigerian prospection material with up to 20% K/F. Table 5.15 shows that the heritability of K/F is generally quite high. However, the low heritabilities for WM/F and S/F when parents and offspring are of different fruit forms (Table 5.12) imply that heritability for K/F would also be low in that situation (Okwuagwu, 1988).

Oil yield: Only a few authors have calculated heritabilities for oil yield. This may seem surprising, given the practical importance of oil yield, but the aim in breeding is usually to cross palms with complementary yield components, so concentration has been on the inheritance of those components, rather than of the final product. Soh (1986) found broad sense heritability values for oil yield ranging from 0.14 to 0.26 in four D $\times$ P trials in Malaysia. Ahiekpor and Yap (1982) found a narrow sense heritability of 0.27 in one trial, but in three others the values were negative. Baudouin and Durand-Gasselin (1991) found broad sense heritabilities, from clone-ortet regressions, ranging from 0.41 to 0.53 in four trials, but Cochard *et al.* (1999) found lower values, from 0.28 down to 0.0 (indicating no genetic variation), from three other clone trials.

5.3.3.3 Other fruit characters

The main fruit types (external appearance) and fruit forms (internal structure) have been described in Chapter 2. The classification developed in Congo is generally accepted, and is set out in Table 2.1.

Virescens fruit: The variations within the *nigrescens* and *virescens* types, and their colour changes during ripening, are discussed in Chapter 2. In *virescens* fruit (Plate VIB) the absence of anthocyanin does not appear to be absolute; there is evidence of traces of an anthocyanin which may be distinct from that normally encountered in the ordinary fruit (Hartley, 1988, p. 237). It appears that the *virescens* character is controlled by a single dominant gene. When one allele of a gene is dominant, only one such allele is needed for the full expression of the character; the phenotype of the heterozygote, in this case *Vir/vir*, is the same as the dominant homozygote (*Vir/Vir*; note that the dominant allele is conventionally written with a capital letter, and the recessive allele without). Only the *vir/vir* genotype fails to express the character.

The number of *virescens* palms found in natural populations is so small that the gene might normally be expected to be found in the heterozygous condition. In Congo, a *virescens* palm, assumed to be heterozygous, gave 75% *virescens* when selfed and 50% when outcrossed (Beirnaert and Vanderweyen, 1941). In Nigeria, an open-pollinated *virescens* bunch gave 46% *virescens* and 54% *nigrescens* (Hartley, 1988). These figures are consistent with a dominant gene.

Mantled fruit: This character has already been described (Section 2.2.2.6), and appears to be due to a single dominant mutation (Plate VIIC, D). Some mantled palms in Congo gave 100% mantled progeny when selfed; others gave 75%, while crosses between mantled and ordinary palms gave 50% mantled (Hartley, 1988, p. 238, quoting Nigerian Conference, 1949). In Nigeria, open pollinated mantled *tenera* palms also showed approximately 50% of each type in their progeny, and Zeven (1973) quotes other open-pollinated progenies in support of dominance. In Sumatra, although most results supported dominance, two mantled selfs gave only 50% mantled progeny instead of the expected 100 or 75%. This could be explained by contamination, but other anomalous results were the appearance of 25% mantled palms in a normal *tenera* self, and the sudden change of an ordinary *tenera* to the production of mantled-fruited bunches (Janssen, 1959; Pronk, 1955). The occurrence of mantled fruit in clonal palms, and the non-Mendelian pattern of inheritance in such material, are discussed in Chapter 6.

At one time the mantled character was thought desirable, as more mesocarp/bunch was expected with it (Schmöle, quoted by Janssen, 1959; Zeven, 1973). D.J. Osborne (pers. comm., 1991) has also pointed out that abscission of mantled fruit is delayed, which might be advantageous for harvesting. However, bunch failure can be a problem with genetically mantled palms (Janssen, 1959), just as it is with clonal palms, and plant breeders now regard mantled fruit as an aberrant type, not to be included in a breeding programme.

5.3.4 Vegetative characters

Marked differences in vegetative development and leaf habit have always been apparent in the oil palm, but in the early years of oil palm research few systematic studies were done. De Berchoux and Gascon (1965) showed the wide differences existing between populations. They studied a Deli progeny from Johore Labis Estate (Socfin, Malaysia), a La Mé T × T cross, and a cross derived from Yangambi, all growing at La Mé in the Ivory Coast. Forty-two to 50 palms per progeny were studied. The Deli had fewer but longer, wider and heavier leaves, more leaflets and wider petioles than the African material. Comparing the La Mé and Yangambi progenies, about the same number of leaves were produced by both progenies, but the Yangambi progeny's leaves were about 40% heavier, and the weight and number of leaflets approached those of the Deli (although the rachis was lighter). Leaf length was, however, no greater in the Yangambi than in the La Mé progeny.

5.3.4.1 Vegetative dry matter production

Following the development of non-destructive growth analysis techniques in Malaysia (see Chapter 4), more extensive studies of growth and of physiological parameters have been undertaken. There is considerable quantitative variation in all characters studied; heritability estimates are summarised in Table 5.16. Various authors have advocated selecting for reduced vegetative vigour and higher harvest index (Corley *et al.*, 1971b; Hardon *et al.*, 1972; Rosenquist *et al.*, 1990; Dumortier and Konimor, 1999). Corley (1973b) showed that maximum total dry matter production was attained at very high planting densities, and argued that, to take advantage of this, palms with a high bunch index (high proportion of total dry matter going to bunches) were needed. This subject is discussed further in Section 5.4.4. The value of selection for traits such as photosynthetic conversion efficiency (e , see Section 4.1.4.3), which are derived by combining several different measurements, has been questioned (see discussion in *Proc. Workshop Progress of Oil Palm Breeding Populations*, Palm Oil Res. Inst. Malaysia, 1990). It was argued, with some justification, that it will be more efficient to select for the component traits (in the case of e , the important traits are yield and leaf area).

5.3.4.2 Palm height

Reducing height has always been of interest to oil palm breeders, because of the high cost of harvesting tall palms. Table 5.16 shows that height has a reasonable

Table 5.16 Heritabilities of growth measurements and physiological parameters

Location	Material	h^2	VDM	Leaf area	BI	LAR	NAR	Height	Ref.
Malaysia	D × T, T × T	h_n^2	0–0.16	0–0.27	0–0.14	0–0.08	0.04–0.08	–	1
		h_b^2	0.14–0.23	0–0.31	0.20–0.26	0.12–0.34	0.04–0.22	–	
Malaysia	Deli <i>dura</i>	h_n^2	–	–	0.33	–	–	–	2
		h_b^2	0.36	–	0.33	0.66	0.44	–	
PNG	2 D × P trials	h_n^2	0.21–0.63	0.69–0.85	0.33–0.34	0.66–0.68	0.32–0.55	–	3
	3 studies	h_b^2	0.81–0.88	0.70–0.82	0.19–0.57	0.54–0.81	0.19–0.41	–	
PNG	D × P	h_n^2	0.19	0.20	ns	0.33	–	0.46	4
Malaysia	D × P	h_n^2	–	–	–	–	–	0.49	5
Malaysia	D × P	h_n^2	0.24	0.13	0.20	0.83	0.21	0.13	6

h_n^2 : narrow sense heritability; h_b^2 : broad sense heritability.

VDM: vegetative dry matter; BI: bunch index; LAR: leaf area ratio; NAR: net assimilation rate.

References: 1: Hardon *et al.* (1972); 2: Ooi (1978); 3: Breure and Corley (1983); 4: Breure and Bos (1992); 5: Soh and Chow (1993); 6: Tan (1978).

heritability. Sparnaaij *et al.* (1963a) listed several specific sources of material with low height increment; these included the Malayan Dumpy E206 (Section 5.1.1.2), the Pobé Dwarfs (Section 5.1.3.1), the Yangambi palm 16R (Section 5.1.2) and *Elaeis oleifera* (Section 5.5.1.6). At one time or another, breeding programmes have been undertaken with all of these, but all have disadvantages which offset their low annual height increment. The Dumpy had poor yield and bunch composition, the Pobé Dwarfs have very poor bunch composition, 16R gave offspring which were low yielding and highly susceptible to *Fusarium* wilt, and *E. oleifera* has very poor oil to bunch. Inheritance of height in Dumpy crosses was mentioned in Section 5.1.1.2. Recently, certain populations within the PORIM Nigerian collection have excited interest because of their small annual height increment (Rajanaidu and Jalani, 1994a). However, crosses between this material and current breeding material were only about 5–10% shorter than standard crosses (Sharma, 1999; Bilal *et al.*, 1999).

Selection for yield will tend to favour taller, and hence more competitive palms, unless efforts are made to avoid doing so. Corley and Lee (1992) found that selected Deli *duras* were 15–22% taller at the same age than unselected material (planted at the same time, under identical conditions; see Table 5.29). Soh and Chow (1993) showed that, using index selection (Section 5.4.1) significant reduction in height increment could be obtained without sacrificing yield, but Dumortier (2000) found a significant positive correlation between progeny means for yield and height. Palms selected for high bunch index, rather than for high yield (Section 5.4.3.1), will tend to be shorter than average, but deliberate selection for reduced height increment is difficult to justify, if it has to be at the expense of yield. In economic terms, any reduction in yield represents a loss from the moment production starts, whereas the advantage of reduced height increment is only seen after many years, when height starts to have an effect on harvesting cost.

5.3.4.3 Resistance to wind

With the extension of oil palm growing into higher latitudes the resistance of the stem and stem base to strong winds has assumed some importance. In general, the palm stands up well to the winds preceding tropical storms in West and Central Africa and South-east Asia. Oil palms of all ages survived the severe force of hurricane Fifi in Honduras in 1974, when adjoining banana plantations were completely flattened (Hartley, 1988, p. 240). In Colombia a tornado in the Magdalena valley

in 1968 demonstrated that there were distinct progeny differences in resistance to high winds (Taillez and Valverde, 1971). In general, Deli × La Mé progenies were less disturbed than Deli × Yangambi progenies. Most affected were palms of 2.5–4.5 years of age in the field. At all ages there was a significant correlation between height of trunk and the amount of disturbance (measured by the angle of inclination). This provides an additional reason for breeding palms with low height increment.

5.3.4.4 Other vegetative characters

One vegetative character which appears to be controlled by a single gene is the *idolatraca* type, in which the leaflets remain fused together (Plate 2.3). Control by a dominant gene was suggested by the fact that an open-pollinated bunch from an ordinary palm in Congo which had an *idolatraca* neighbour gave 17% *idolatraca* progeny. Of 34 progeny of a selfed *idolatraca* in Congo, 20 were *idolatraca* (Beirnaert and Vanderweyen, 1941). Intermediate forms were found in Nigeria, but controlled pollinations there also indicated dominance (Hartley, 1988, p. 239). A selfed *idolatraca* palm in Sumatra bred true (Fickendey, 1944), and this was suggested as indicating that the character might be recessive (Hartley, 1988), but without knowing the ancestry of the palm, there is no obvious reason why it should not have been homozygous for a dominant gene.

Occasional selfings include 25% of albino seedlings (V. Rao, pers. comm., 2001), indicating control by a recessive gene. Such plants have no chlorophyll, so are unable to photosynthesise, and die once the kernel food reserves are used up.

5.3.5 Disease resistance

There are several diseases and disorders for which genetic variation in susceptibility or resistance has been demonstrated. Breeding for resistance has been most successful with *Fusarium* wilt (Plate VID); methods and results of nursery selection for wilt resistance are discussed in detail in Section 12.1.6.2. There is still some debate as to the genetics of resistance to this disease. Meunier *et al.* (1979) found parents which consistently gave crosses with a high degree of tolerance, and considered that tolerance was polygenic, but de Franqueville and de Greef (1988) suggested that it may be controlled by only two genes. The latter authors produced hypothetical genotypes at these two loci for a large number of parents in the Binga programme, but attempts to test their hypothesis with further crosses

were hampered by the death, from wilt, of all the most susceptible genotypes. Renard *et al.* (1993) reported that resistant clones could be obtained from progenies which, based on average performance, were susceptible and vice versa; this suggests segregation of a simple character, rather than additive inheritance. In practice, though, it may not be possible to distinguish between the two-gene hypothesis of de Franqueville and de Greef and additive inheritance. Two loci, each with two codominant alleles, give nine possible genotypes; if we superimpose on these variation due to incomplete infection by the disease, the result will have the appearance of continuous variation. An unsuccessful search for molecular markers linked to wilt resistance has been made (Buchanan, 1999).

Trials in Nigeria showed differences between progenies in susceptibility to patch yellows (see Section 12.1.5.5), which is caused by a different strain of *Fusarium oxysporum* from that causing wilt (A.G. Prendergast, pers. comm., 2001). There is some evidence for genetic resistance to *Cercospora elaeidis* (Section 12.1.2.1), but breeding for resistance to this disease does not appear to have been attempted, although Duff (1970) showed that it could depress yields by more than 10% over the first 7 years of production. The resistance of *E. guineensis* × *E. oleifera* hybrids to marchitez sorpresiva (Section 12.1.6.5) and fatal yellowing (Section 12.1.7.2) in South America should also be mentioned (see also Section 5.5.1.6). Most claims for genetic resistance to *Ganoderma* basal stem rot, the predominant disease in the Far East (Section 12.1.6.3), have been unconvincing, but Durand-Gasselin *et al.* (1999c) reported differences between clones in susceptibility, and de Franqueville *et al.* (2001) showed significant differences between families for *Ganoderma* incidence in Indonesia.

Crown disease may also be mentioned here; it is questionable whether this vegetative disorder is really a disease, and severity is strongly dependent on environment, but it is clear that susceptibility is inherited. De Berchoux and Gascon (1963) showed that susceptibility

was controlled by a single recessive gene, but Blaak (1970b) found unexpected segregations in some crosses, despite correct fruit-type segregation indicating that the crosses were probably legitimate. He explained his results by postulating a second gene which, when homozygous, suppresses expression of the disorder. This is discussed in more detail in Section 12.1.5.1.

5.3.6 Stress tolerance

5.3.6.1 Drought tolerance

Despite its probable origin as a species of wet soils on river banks (see Section 1.1.3), the oil palm is a drought-tolerant crop, surviving in parts of West Africa with a dry season of several months. However, in the most severe dry seasons, death, particularly of young palms, may occur. In less severe climates, the effect of drought on bunch yield may be large, and the possibility of breeding for drought tolerance has been under consideration for some time. Before this can be done, though, drought tolerance must be defined. In Benin, where palm death in the dry season is common, tolerance has been equated with survival (Houssou *et al.*, 1989), but in less severe environments, a more useful definition would be the ratio of yield under drought to yield without drought.

Maillard *et al.* (1974) measured a drought 'sensitivity index', SI; this was simply a numerical assessment of the drought effects recorded in a population or progeny, using the formula:

$$SI = (10M + 5S_3 + 3S_2 + 2S_1)/N \quad (5.8)$$

where N = total number of palms, M = number of dead palms, S_1 = palms showing an accumulation of unopened spears, S_2 = palms with four to six leaves broken or collapsed, and S_3 = palms with all lower leaves withered. Differences between progenies in SI were apparent, but there was no clear evidence that these had a genetic cause and were not just due to chance.

Houssou *et al.* (1989) demonstrated genetic differences in survival between progenies in Benin. Table 5.17

Table 5.17 Yield and mortality in Republic of Benin

Type of cross	No. of crosses	Deaths by 10th year (mean ± SD)	Yield of oil (t/ha per year) based on	
			143 palms/ha	Surviving palms
Deli × La Mé	11	22.5 ± 12.8	1.30	1.07
Deli × Yangambi	12	3.5 ± 4.2	1.03	1.00

From Houssou *et al.* (1989).

Yields are means for years 6–10 after planting.

shows that Deli $\times$ La Mé crosses, although potentially higher yielding, suffered a significantly higher death rate than Deli $\times$ Yangambi crosses. The yield from surviving palms was not much higher from Deli $\times$ La Mé than from Deli $\times$ Yangambi.

These results illustrate a problem with breeding for drought tolerance: when severe drought is an irregular occurrence, a compromise may have to be made between drought tolerance and yield in years with less severe drought. However, Houssou *et al.* (1989) did find some progenies that both yielded well and had low mortality. A question then is whether such progenies can be identified at an early stage. Maillard *et al.* (1974) tried to develop methods of measuring drought resistance in young palms. They looked at root growth of seedlings under high osmotic pressure, using polyethylene glycol, and at tolerance of high temperature, but agreement between these methods was not very good.

Cornaire *et al.* (1989) considered stomatal opening, leaf water potential and membrane breakdown as possible selection criteria. They found that a low-yielding but drought-tolerant cross had fewer open stomata under drought than higher yielding but susceptible crosses, and had higher leaf water potential and less membrane damage. Cornaire *et al.* (1994) found that progenies with better root development tended to have greater drought resistance. They also discussed photosynthetic rates, mobilisation of starch reserves, membrane damage and protein breakdown. Lamade *et al.* (1998b) studied photosynthetic rate and other physiological parameters for three different clones under drought conditions. Smith (1993b) found significant differences between families in stomatal opening and photosynthetic rate during the dry season in Congo, and suggested that these parameters might be used to select for drought tolerance (see also Section 4.3.3.2).

Despite all this effort, a reliable method of selecting drought-tolerant material remains elusive, and Nouy *et al.* (1999) remained circumspect about the prospects for drought resistance breeding, suggesting that there was no justification for changing breeding programmes.

5.3.6.2 Low-temperature tolerance

As discussed in Chapter 3, the oil palm grows poorly at temperatures much below 20°C, and this restricts the latitude and altitude ranges over which the crop can be grown. In 1966, Blaak collected palms from groves in the Bamenda Highlands of Cameroon, at altitudes of 1000–2000 m asl; in 1977, he also collected material from about 1000 m asl in Tanzania. D $\times$ P progenies derived from these collections were tested at 960 m asl in

Ethiopia (Blaak and Sterling, 1996). Bamenda $\times$ AVROS and Tanzania $\times$ AVROS crosses were more precocious, with 70% and 62% of palms flowering 12 months after planting, than Deli $\times$ AVROS (3%) or Deli $\times$ Ekona (37%). This indicates the possibility of low-temperature tolerance, and other trials have been established at similar altitudes in Uganda, Zambia and Malawi. As yet, no yield data from these trials have been published.

5.3.7 Oil composition

Interest in modifying the fatty acid composition of palm oil arises primarily from the fact that, after fractionation, the liquid, olein fraction usually fetches a higher price than the solid, stearin fraction. This is discussed further in Chapter 14, but breeders have taken the view that increasing the proportion of olein would be a useful objective. There are three distinct ways in which this might be done: by using the variation observed in *E. guineensis*, by hybridisation with *E. oleifera* or by genetic engineering. The first two options are discussed below; genetic engineering is considered briefly in Chapter 6.

5.3.7.1 Oil composition and *Elaeis oleifera* hybrids

Palm oil of *E. oleifera* has more unsaturated fatty acids (oleic and linoleic) and a higher iodine value (IV, a measure of unsaturation) than *E. guineensis* (Table 5.18), and is quite similar to olive oil in composition. Early work indicated that the oil of the interspecific hybrid was intermediate (Hardon, 1969), indicating additive inheritance, and this was confirmed by Meunier and Boutin (1975), Macfarlane *et al.* (1975) and Ong *et al.* (1981). The last study showed that the oil composition in hybrids was intermediate between the two species, and that back-crosses between hybrids and either parent gave, in turn, oil intermediate between the hybrid and the back-cross parent. Triglyceride composition of the oil followed the same trends. Back-crosses are expected to be highly variable, though, and Sharma and Tan (1997) found individual F1 $\times$ *E. guineensis* back-cross palms with IVs of up to 76. Ong *et al.* (1981) argued that both fatty acid levels and triglyceride structure were controlled by a single, codominant gene. Their data were equally consistent with additive inheritance of quantitative characters, but the pathway of fatty acid synthesis is fairly simple (see Section 6.6.2.1) and it is conceivable that changes in a single gene could alter the levels of all the main fatty acids.

Table 5.18 Composition of oils from *Elaeis guineensis*, *E. oleifera* and their hybrids

Fatty acid		<i>E. guineensis</i>	Hybrid	<i>E. oleifera</i>	Back-cross to <i>E. guineensis</i>
Palmitic	C16:0	27–64	27–41	17–30	35–41
Stearic	C18:0	1–13	1–6	0.2–2	1–5
Oleic	C18:1	23–54	43–59	54–69	43–48
Linoleic	C18:2	2–18	8–15	5–22	9–14
Iodine value		32–65	58–71	70–93	58–62

Data are ranges, mostly for individual palms, from various sources, summarised by Corley (1979); also Ong *et al.* (1977, 1981), Sharma *et al.* (1994), Sharma (1999) and Rajanaidu *et al.* (1989).

Table 5.19 Composition of kernel oils from *Elaeis guineensis*, *E. oleifera* and their hybrids

Fatty acid		<i>E. guineensis</i>	<i>E. guineensis</i> × <i>E. oleifera</i>	<i>E. oleifera</i> × <i>E. guineensis</i>	<i>E. oleifera</i>
Caprylic	C8:0	2–6	2–6	3	1–2
Capric	C10:0	2–7	3–5	3	1–2
Lauric	C12:0	41–55	46–52	31	27–30
Myristic	C14:0	14–19	18–20	22	26
Palmitic	C16:0	6–11	6–9	10	10–11
Stearic	C18:0	0.5–5	1–2	2	2
Oleic	C18:1	10–20	10–16	25	25
Linoleic	C18:2	0.4–5	2–3	3	4–6

Data are ranges, mostly for individual palms, from various sources, summarised by Corley (1979); a single sample for *E. oleifera* × *guineensis* from Meunier *et al.* (1976).

Ong *et al.* (1977) obtained an average of 67% olein from 35 samples of *E. guineensis* oil, and 79% and 88% from two interspecific hybrid oils, confirming the expected advantage of the hybrids for fractionation. These hybrids are further discussed in Section 5.5.1.6.

5.3.7.2 Variation in oil composition in *Elaeis guineensis*

Ng *et al.* (1976) and Corley (1979) compared the possibilities of modifying palm oil composition by selection within *E. guineensis* and through the interspecific hybrid, and drew attention to the fact that *E. guineensis* itself varies appreciably in oil composition, with both *pisifera* and *albescens* palms giving oils with high linoleic content. Studies of heritability and repeatability of oil composition have shown contrasting results, but Gascon and Wuidart (1975) found significant repeatabilities with 20 crosses in oleic and linoleic acids, and suggested that increases of 8–12% in unsaturated acid content by selection and breeding are feasible in *E. guineensis*.

Particular attention was paid to oil composition in the evaluation of the PORIM Nigerian prospection

material (see Section 5.1.6.2). Individual palms with IV over 64% have been identified (Rajanaidu *et al.*, 1989), and these are being used in breeding programmes to develop high IV lines. However, data presented by Rajanaidu and Jalani (1994a), often quoted as showing that offspring of high IV palms inherit the characteristic, actually showed a negative (although not significant) correlation between parent and offspring IVs. The iodine values for the offspring were high, but this might be explicable if samples were taken as soon as fruiting started (the age at sampling was not given). The iodine value of oil from palms in the first year of bearing tends to be higher than in later years (Corley, unpubl.); this complicates studies of oil composition, and care must be taken to avoid drawing premature conclusions. At present, the possibility of making large changes in IV by breeding remains unproven.

5.3.7.3 Composition of kernel oil

Variation in kernel oil composition in *E. guineensis* has received little attention; data from various sources are summarised in Table 5.19. Kernel oil of *E. oleifera* has

a higher myristic and oleic, and lower lauric, content than that of *E. guineensis*. Meunier *et al.* (1976) found that hybrid kernel oil resembled that of the female parent. This suggests maternal inheritance; in most species (oil palm has not been studied), endosperm or kernel is triploid, receiving one set of chromosomes from the male parent and two sets from the female. The results of Meunier *et al.* (1976) could thus be explained by a form of 'dominance', in which the oil composition depends on the duplicated chromosome set (see also Section 5.3.3.1, *Dura and tenera shell thickness*, where a similar effect may occur).

5.3.7.4 Carotene content

The *albescens*, or 'white-fruited', type usually contains less than 60 ppm carotene in the oil, although as much as 90 ppm is sometimes found. It was noted in Congo that open-pollinated *albescens* gave either no *albescens*, or only 1–5%, in the progeny, so it was assumed that absence of carotenoids was a recessive character (Vanderweyen and Roels, 1949). There was some interest in *albescens* material in the past, for its low carotene content, but in practice good-quality palm oil is easy to bleach, so breeding for low carotene did not appear worthwhile.

Recently, there has been interest in high carotene (Rajanaidu *et al.*, 2000b), for its nutritional value. Within non-*albescens* fruit, there is quantitative variation in carotene content. According to Rajanaidu *et al.* (2000b), Deli *duras* averaged about 500 ppm carotene, whereas the mean for the Nigerian prospection material (Section 5.1.7.2) was over 900 ppm. In crosses derived from the Nigerian material, the range for individual palms was from 180 to 2500 ppm. Another source of high carotene palm oil is *E. oleifera* and hybrids.

5.4 METHODS OF SELECTION AND BREEDING

5.4.1 Breeding objectives

The main selection criteria used have been discussed in Section 5.3. However, the emphasis to be placed on different criteria needs to be decided. Falconer (1981) noted that, when selection for several characters is required, this can be done in at least three ways. First, one could select for each character in turn, in successive generations; this would clearly be very slow, with the long generation time of the oil palm. The next approach, known as 'independent culling levels', is to select for all characters simultaneously but independently, rejecting all individuals that do not come up to

standard for all characters. The third, and theoretically most efficient, approach is 'index selection'; this involves selection for an index which combines all characters, with each being weighted according to both its heritability and its economic value. The main contribution to the index would thus be from characters that were both highly heritable and economically valuable; characters that were of high value but poorly heritable, or heritable but of low value, would receive less emphasis. The index selection approach has been adopted for the oil palm by one group in Malaysia (Soh and Chow, 1993; Soh *et al.*, 1994a; Soh, 1999), but most oil palm breeders appear to have used a rather lax version of independent culling levels, under which standards for several traits are applied, but a palm might be selected if it were particularly outstanding for one trait, even though it failed to reach the standards for other characteristics.

5.4.1.1 Bunch yield or bunch quality?

The move from *dura* to *tenera* planting material gave an increase in oil production of around 30% (Section 5.3.3), but further improvement of this order within the *tenera* is likely to be much more difficult to achieve, and it has therefore been argued that more benefit is to be gained from improving bunch yield. Van der Vossen (1974) showed that, if each component of oil yield were to be increased separately by its standard error, then the returns from increases in either number or weight of bunches would be five to 13 times greater than the returns from increases in fruit to bunch, mesocarp, mesocarp oil or kernel oil. However, selection progress depends not only on the variation available, but also on the heritability (Section 5.5.2.1). Van der Vossen's material showed high heritabilities for fruit components but low heritability for bunch yield, in agreement with general trends (see Tables 5.9 and 5.15), so selection progress would be slower for bunch yield than for fruit composition. Thus, it is doubtful whether useful economic conclusions could be drawn from the data, and in practice, there is no reason why the breeder should not pay attention to both bunch yield and bunch quality.

5.4.1.2 Oil or kernels?

In contrast to bunch yield and quality, these two objectives are to some extent mutually exclusive; an increase in one will often be at the expense of the other. Hartley (1988) maintained that the kernel had been neglected by oil palm breeders since the days of Beirnaert (1933c), who had included it as one of his selection

criteria. Broekmans (1957a) emphasised the kernel with the introduction of his 'C factors': C1 was the content of kernel plus mesocarp to bunch, i.e. $(1 - \text{shell/fruit}) \times \text{F/B}$. However, although generally appearing in tables of fruit composition, K/B has seldom been a positive objective in breeding.

Hartley (1988, p. 257 *et seq.*) and Rajanaidu and Jalani (1994b) have argued that breeding for high K/B, and correspondingly lower O/B, would give a better return than high O/B with low kernel, but the case depends on relative prices of the two commodities. Hartley assumed prices of US\$500/t for oil and \$400 for kernel; Rajanaidu and Jalani used 1992 prices, which were \$366 and \$263, respectively. The ratios of kernel to palm oil prices in these two studies were 0.8 and 0.72, but Rajanaidu and Jalani also presented average prices from 1980 to 1992, showing a ratio of only 0.61. If this ratio is substituted in the calculations, the benefits of breeding for high kernel are very small. A further problem with the argument is the assumption that K/F can be increased, from 5% to 10% for example, without change in shell/fruit. Hartley (1988) did quote examples of two palms, one with 6% K/F and one with 13%, both with 8% shell, but in general, if kernel size is increased, the percentage of shell to fruit will also be increased. A point in favour of kernel is that factory kernel extraction is usually more efficient than oil extraction, so actual yields will come closer to the bunch analysis figures for kernel than for oil.

Hartley (1988) drew the following conclusions.

- Oil to mesocarp is of great importance; an increase from 50 to 55% will appreciably reduce the advantage that kernel has over mesocarp. Conversely, oil percentages of less than 50% are disadvantageous and fruit with large kernels would in this case be preferable.
- It is probably not possible to reduce shell percentage to as low a figure in high-kernel *tenera* as in high-mesocarp *tenera*; even the thinnest shells usually constitute 50% of the nut weight. Therefore, the highest mesocarp plus kernel percentage will be obtained from high-mesocarp fruit. If this can be combined with oil to mesocarp well above 50%, this type of fruit is likely to give the highest gross return.

Perhaps the most important conclusion is simply that the breeder must not forget about the kernel. Some breeders look at yield of (oil + kernel), but this does not allow for the lower value of kernel. Donough and Law (1995) and Rajanaidu *et al.* (1998b) used (oil + 60% of kernel); this approximates to the long-term relative market values, as noted above.

5.4.2 Choice of breeding method

As noted in the introduction, there appear to have been two main influences on oil palm breeding: maize breeding and animal breeding. The oil palm is monoecious and is naturally cross-pollinated; the most important other monoecious crop is maize. The general approach of maize breeders has been to try to concentrate complementary and desirable characters in inbred lines, followed by the crossing of these lines to provide homogeneous F1 hybrids, with resulting hybrid vigour. RRS has been extensively used in maize, and many oil palm breeding programmes are essentially based on this approach, as discussed below.

Oil palm breeding also has several features in common with animal breeding. Although both parents have male and female flowers, for seed production the *dura* has taken on the role of the mother palm and the *pisifera* that of the father. Sterile *pisiferas* must be selected for potential fruit production by progeny testing, in an analogous way to, for example, the selection of bulls for milk yield in cattle. With annual crops there is usually no possibility of using the parents after the performance of the progeny has been noted, but with animals and with the oil palm the parents can be re-employed for many years. RRS has been used with poultry, but the most common approach in animal breeding is probably FIS. In oil palm breeding, there has long been a debate between advocates of FIS and of RRS. FIS tends to use phenotypic selection, based on the actual performance of individual palms, while in RRS there is more emphasis on breeding values determined by progeny testing, but as will be seen this is not a clear distinction. The theoretical and practical merits of alternative methods are discussed below [see also reviews by Soh (1987, 1999)]. The progress made in some breeding programmes is assessed in Section 5.5.2.

5.4.2.1 Reciprocal recurrent selection

The first oil palm programme which approximated to RRS was planned at Yangambi by INEAC. The first phase of this programme consisted of a diallel cross between six *teneras* (Pichel, 1956), the intention being that high-yielding T × T combinations from this programme could be reproduced by combining *duras* in the selfed progeny of the one *tenera* with *pisiferas* in the selfed progeny of the other.

Subsequently, both NIFOR in Nigeria and IRHO in the Ivory Coast based their programmes on RRS (Sparnaaij *et al.*, 1963a; Gascon and de Berchoux, 1964). A simplified diagram of the IRHO (CIRAD-CP)

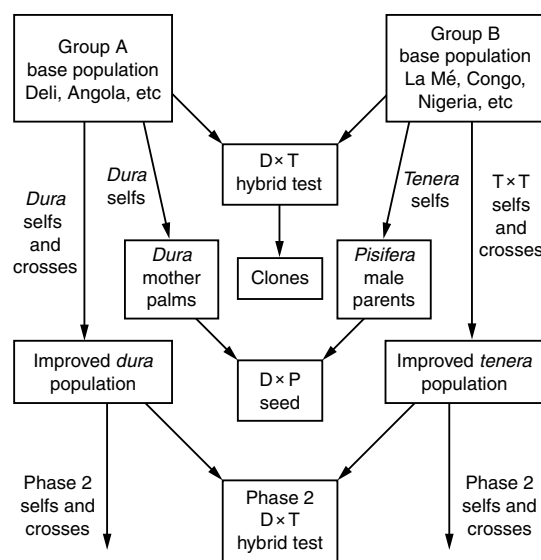


Fig. 5.10 Simplified diagram of CIRAD recurrent reciprocal selection programme. (Redrawn from Baudouin *et al.*, 1997.)

programme is shown in Fig. 5.10. The key points are as follows.

- There are two base populations: in the CIRAD programme, 'A' consisted of Deli *duras* from several origins, and 'B' of *teneras* and *pisiferas* mainly from La Mé and Yangambi.
- $D \times T$ and $D \times P$ test crosses are made between the two populations.
- The parents of the best individual crosses from the test-cross programme are selfed (or in the case of sterile *pisiferas*, *tenera* sibs are selfed), and *dura* and *pisifera* palms within these selfings are used for seed production, 'reproducing' the selected test crosses. The expectation is that both GCA and SCA effects will be reproduced.
- Selfs and crosses among the best individuals within the two populations form the next generation, from which test crosses are made and the cycle is repeated.

In the CIRAD programme, there has been a preference for crosses rather than selfings to give the phase 2 populations (Durand-Gasselin *et al.*, 1999b). In the NIFOR programme selfing is apparently preferred.

In favour of RRS, it has been argued that, although mass selection may give progress for the more heritable characters, for the important but less heritable

characters such as bunch yield it is probable that marked non-additive genetic variance is involved (Meunier and Gascon, 1972; Noiret *et al.*, 1966). Analysis of data from the NIFOR programme showed significant deviation from additivity for both bunch yield and mean bunch weight, although number of bunches was found to have a fairly high additive component. West *et al.* (1977) found several progenies which produced much higher or much lower yields than predicted from additive inheritance alone, and they considered that, for bunch yield and mean bunch weight, the use of the *dura* $\times$ *tenera* comparative trials was essential. These results were held to support the claim of Meunier and Gascon (1972) that selection methods which took only additive genetic variance into account would neglect real advances to be made through utilising specific combining ability. RRS should permit the exploitation of specific combining ability as well as general combining ability, although Baudouin *et al.* (1997) made the point that the number of possible combinations can become too large to be manageable, and that selection may, in practice, be mainly for GCA.

Hardon outlined some arguments against the use of RRS (Hardon, 1970; Hardon *et al.*, 1973). The need to keep two populations separate, and the limited number of parents in the base populations that can be tested, mean that some inbreeding in the two populations may be unavoidable, and may result in random loss of genetic variability, while the alternate cycles of progeny testing and selection may cause gene frequencies to oscillate rather than show progress. Rosenquist (1990) noted the small numbers of palms included in the base populations of RRS programmes, and estimated that, with fixed resources for trials, two to three times more palms from a base population could be evaluated by FIS than by RRS. Soh (1987) considered that the large populations required mean that RRS is more appropriate for large national or international organisations than for small seed producers.

According to Griffing (1963), ideally the two populations for RRS should be obtained by arbitrarily dividing the base population into two; clearly, this is not what has been done in oil palm, where Deli *dura* and Africa *tenera* populations with contrasting characteristics have been the starting material. Against this point, Baudouin *et al.* (1997) argued that the initial choice of two populations with distinct and complementary characteristics was itself a source of immediate progress. This was presumably a reference to the improved yield obtained from 'interorigin' crosses compared with intraorigin (Gascon *et al.*, 1966). However,

Hardon (1970) contended that this effect was simply due to out-crossing partially inbred populations (Section 5.4.3).

A disadvantage of RRS is the extended 'generation time'; because interpopulation crosses must be tested before the parents for the next cycle can be selected, one cycle effectively occupies two generations. This problem can be minimised if selfings of all parents are made at the same time as the interpopulation test crosses, but the saving in time is at the expense of a greater land area for trials. In the IRHO/CIRAD programme, some, but not all, parents are selfed at the same time as, or a few years after, the test crosses are made (Durand-Gasselin *et al.*, 2000a).

5.4.2.2 Family and individual selection

This system is very simple: the best families are chosen, and within those the best individuals are selected. Individual selection should be based on characters with high heritability, while those with lower heritability are emphasised in the family selection stage. The approach advocated by Hardon (1970) was to increase variability by crossing between origins, and by introducing new germplasm, followed by mass selection of families and individuals, avoiding inbreeding, and emphasising GCA. While extensive collections of new germplasm have been made since then (Section 5.1.7), few attempts have yet been made to use this material to increase diversity in breeding populations, and commercial seed still consists predominantly of Deli *duras* crossed with Congo or La Mé *pisiferas* (see Section 5.1.7; also Rajanaidu and Jalani, 1999b).

As *pisiferas* cannot be selected on their phenotypic performance, a progeny-testing stage has usually been introduced (Section 5.4.2.3). As a result, programmes based on FIS may come to bear a distinct resemblance to RRS programmes, and some have been described as 'modified recurrent selection' (Soh, 1987, 1999; Rajanaidu *et al.*, 2000a). As Meunier (1989) pointed out, the argument between the two approaches is largely an academic one, and in most breeding programmes, both types of selection are used at one time or another, although there may be differences in the relative importance accorded to general and specific combining abilities. Differences between the systems are further diminished by the preference for crosses rather than selfings within the two groups in the CIRAD programme (Durand-Gasselin *et al.*, 1999b), and the use for seed production of individual tested *pisiferas*, as well as untested *pisiferas* from selfings of selected *teneras* (Durand-Gasselin *et al.*, 2000a).

Durand-Gasselin *et al.* (1999b) described the two approaches as having 'merged', with Deli *dura* and *tenera/pisifera* populations being kept distinct in all programmes. However, this distinction is not always made; in some instances, both *duras* and *pisiferas* may be selected from $T \times T$ crosses, care being taken to avoid inbreeding (e.g. Porter, 1989).

There is a difference between the methods in the approach to production of seed for commercial plantings. With FIS, individual *duras* are selected on their phenotypic performance, and *pisiferas* either by family, on the performance of their *dura* and *tenera* sibs, or after a further generation of progeny testing. In the RRS system of CIRAD, in contrast, seeds are produced as crosses between selfings of palms identified from the test crosses; in effect, families of selfs are selected by progeny testing of their parents. Phenotypic selection within the *dura* selfs allows further improvement (Jacquemard *et al.*, 1982), and Durand-Gasselin *et al.* (2002) advocated another generation of selfing of the selected *duras* for use as seed parents, but this is not the most important selection stage. This approach has the commercial advantage that very large numbers of seeds can be produced of single 'reproductions'; these are regarded by seed buyers as 'varieties'. With the FIS system, mass selection may throw up large numbers of unrelated *duras*, so that there is no equivalent of the RRS varieties (other than the broad categories of Deli $\times$ AVROS, and so on).

5.4.2.3 Pisifera selection

The *pisifera*, as the pollen parent, can be used for the pollination of many *dura* bunches, over a long period. From a single male inflorescence 50–100 g of pollen may be collected; by diluting the pollen with talc it is possible to obtain good fruit set with no more than 0.05 g pollen per bunch. With perhaps 1500 seeds per bunch, the area covered by the progeny of one inflorescence from one *pisifera* could be more than 5000 ha, whereas ten bunches from a *dura* parent in a year will only cover about 75 ha. In PNG, five *pisiferas* have been used to produce up to 12 million seeds/year (Dumortier and Konimor, 1999). This alone makes progeny testing of *pisiferas* worthwhile. In seed production programmes, *pisifera* palms that have been shown to produce outstanding *tenera* progenies will still be in use when *dura* seed trees of a later generation are in production. The older generation of *pisiferas* may not be such potentially good parents as some of the *pisifera* of the later generation, but their worth will be more fully known.

Progeny testing is also desirable because the majority of *pisiferas* are more or less female sterile, bearing few or no fertile fruit (see Section 2.2.2.6), and thus cannot be evaluated on phenotypic performance. Selection can be based on the phenotypic performance of *dura* and *tenera* sibs, with FIS, or on the test-cross performance of the *tenera* parent with RRS, but in most programmes, progeny testing of *pisiferas* plays a part. A number of provisionally selected *pisiferas* is each crossed with several *duras*; appropriate crossing programme designs are discussed in Section 5.2.2. Evaluation is best done by calculation of breeding values (Section 5.2.6.3). An additional reason for progeny testing is to confirm that the female-sterile palms are truly *pisiferas*; occasional sterile *duras* and *teneras* also occur and it is of course essential that these should be recognised and not used for seed production. A cheaper and quicker method of checking is to prevent bunch failure by regular spraying with an auxin, so that some fruits ripen and the fruit form can be checked (Obasola, 1973b).

After progeny testing, ideally only the best *pisiferas* will be used for seed production. However, shortage of male inflorescences and hence of pollen may limit their use. Severe pruning has been used by many breeders to try to stimulate male inflorescence production; Durand-Gasselin *et al.* (1999a) showed that this can be very effective.

As partially fertile *pisifera* with high bunch production exist, there has naturally been a desire to measure their yield and make use of them in breeding. Several reasons for employing such fertile *pisifera* have been put forward. First, with fertile *pisiferas* there is no need to check the fruit form by auxin spraying or progeny testing (see above). Secondly, oil to mesocarp contents can be measured in fertile *pisifera*; this perhaps provides the strongest argument for their use. Against the use of fertile *pisifera* are the facts that they are limited in number, that their own bunch yield is no real indication of their power to transmit factors for bunch yield, and that they may be related to thick-shelled *tenera* and carry heritable factors for shell thickness (but see Section 5.3.3.1, *Shell thickness and sterile pisiferas*).

Doubts as to the usefulness of yield data from fertile *pisifera* are engendered by the fact that fertility varies so greatly (Henry and Gascon, 1950). In the Congo prospection of estates, derived largely from *tenera* parents, about two-thirds of nearly 900 *pisifera* identified aborted almost all their fruit (Vanderweyen, 1952b). Of 147 bunches cut from palms setting some fruit the average fruit/bunch was only about 30%. Further analysis of seven palms giving bunches with over 50% F/B

showed that regularly high ratios were not obtained from any palm. However, one remarkable *pisifera*, numbered P21, was found in southern Congo: bunch yield was 127 kg/year, F/B was 67% and the fruit had a large kernel constituting 10.7% of the fruit; 39% germination was obtained from the kernels (Desneux, 1958). In Nigeria, *pisiferas* yielding over 130 kg/year were also found (A.G. Prendergast, pers. comm., 2001). The possibility of breeding pure fertile *pisifera* material is discussed in Section 5.5.1.5.

5.4.2.4 Use of breeding values

Sparnaaij and van der Vossen (1980) recommended that, in breeding for yield, special attention be given to determining genotypic or breeding values of as many promising parents as possible, and that 'transgressive segregation' be exploited by crossing parents with contrasting yield components. Whether or not their 'additive model' of the inheritance of yield components, and the transgressive segregation which it predicts, is accepted (Section 5.3.2), the use of BVs for yield has the attraction of reducing the large area that, under reciprocal recurrent selection, must be given over to $D \times T$ comparisons. Soh (1994) used 'best linear unbiased prediction' to calculate BVs for AVROS and Dumpy-AVROS *pisiferas*, and found that the AVROS *pisiferas* were superior for oil yield, but the Dumpy-AVROS had better BVs for low height increment. Breure and Konimor (1992) estimated BVs for oil yield and its components for 29 *duras* and 14 *pisiferas* from a $D \times P$ progeny trial, and showed how these could be used to predict the yield of crosses that were not included in the trial, provided that additive variation predominates in the material studied.

Dumortier *et al.* (1992) calculated BVs for over 200 parent palms in the Binga programme. Mean values for a number of different origins are listed in Table 5.20. The Ulu Remis Deli *duras* gave good oil + kernel yield, through high mean bunch weight, but Delis from Lofindi were not so good; they had high bunch weights, but below average bunch number, and their BVs for FFB yield were below the mean. The only other origins comparable to the Ulu Remis Deli were the Yangambi family BGY16 (see Fig. 5.4) and Cowan (derived from Unilever's fertile *pisifera* selections in Nigeria, see Section 5.1.3.3). Pure Djongo parents were poor, with negative BV for oil + kernel yield. The best oil/bunch came from Cowan, and from Mongana (local selections in the Binga district). The very low vegetative vigour of the Pobé origin was notable; the La Mé parents also had low BV for VDM, with below average height.

Table 5.20 Mean GCA values for different origins. Data are expressed as differences from mean of standard crosses (%), except for oil/bunch (O/B), which are differences from the actual mean value

Origin	No. of parents	O + K yield	FFB yield	B no.	B wt	O/B	Ht	Bunch index	Wilt index
Population mean		99.5	106.9	110.0	99.1	21.41	101.8	100.5	196
BGY16 ^a	7	16.1	18.2	14.6	4.1	-0.37	3.2	12.2	8
Cowan	3	15.4	-8.3	10.3	-11.9	1.88	-6.3	0.9	-87
Deli (Ulu Remis) ^b	14	14.4	15.9	1.8	13.4	0.14	4.8	4.7	1
Mayumbé	2	7.8	5.2	-2.4	6.3	0.19	0.6	-2.7	29
BGVII ^a	3	6.6	8.0	15.2	-6.2	0.42	3.1	6.3	70
BGY6 ^a	6	6.1	6.0	5.4	1.7	0.13	6.8	2.9	-21
La Mé × Deli	6	5.1	2.0	2.7	-1.6	0.42	-8.8	6.2	-78
Yangambi	10	4.8	2.6	10.2	-7.5	0.13	9.8	2.7	-39
BGY11 ^a	7	4.1	4.6	10.2	-4.5	0.39	8.6	6.9	-31
Djongo × Ngazi (BGY2) ^a	6	-1.3	1.4	-9.5	9.0	-0.27	-1.7	2.1	180
Djongo × Ngazi (BGY3) ^a	6	5.9	7.6	-9.3	13.7	-0.02	6.6	1.1	7
Djongo × Ngazi (BGY8) ^a	6	3.6	2.8	-12.7	13.4	-0.08	-10.0	3.0	9
Djongo × Ngazi (BGY9) ^a	4	7.3	9.3	9.4	-1.4	-0.45	-3.9	3.5	-27
Deli × Yangambi	13	3.3	2.5	-4.7	5.4	0.36	-4.5	-2.0	-37
Djongo × Yawenda	4	2.0	-0.3	2.2	-3.2	1.13	-3.2	0.5	55
Yocoboué	3	0.6	-0.2	-3.1	-0.1	-0.57	-11.6	5.9	-76
Deli (Lofindi) ^b	5	-3.0	-3.3	-17.8	10.3	0.67	-1.8	-5.1	41
Mongana	3	-4.0	-7.9	-4.8	-2.0	1.36	11.4	-6.1	-36
NIFOR (Angola, Calabar)	2	-4.6	-9.6	2.5	-9.3	1.03	-7.2	-1.7	-13
Brabanta	22	-5.5	-6.2	-7.4	0.8	-0.21	-2.6	-6.8	-21
Pindi	22	-6.2	-4.3	-7.0	4.1	-0.28	6.2	-10.9	-11
Ekona	11	-6.8	-1.1	7.4	-8.1	-1.16	3.6	2.1	36
La Mé	8	-9.8	-9.6	-3.0	-6.4	-0.10	-13.7	4.1	1
Djongo (BGY1, BGY4, BGY5) ^b	15	-11.5	-9.4	-2.4	-7.7	-1.00	-6.0	-5.1	44
NIFOR (Aba)	5	-14.1	-13.0	-3.8	-8.6	-0.04	-8.9	-3.6	19
Pobé	4	-19.0	-19.1	7.7	-21.2	-1.75	-31.1	8.0	24

From Dumortier *et al.* (1992).

GCA: general combining ability; O: oil; K: kernel; B: bunch.

^aSee Fig. 5.4.^bSee Fig. 5.1.

BGY16 had the best bunch index, with the Pobé origin also notable in this respect.

5.4.2.5 Inbred lines

In any cross-pollinating species, seedling progenies will be genetically heterogeneous, unless steps are taken to reduce variation. By planting only the best genotypes, useful yield improvements over mixed seedling populations can be obtained. Oil palm breeders have considered developing inbred lines to produce F1 hybrids, as is done with maize. Part of the INEAC programme involved 'purification' by inbreeding to give homozygous *dura* and *pisifera* lines; this is effectively an extension of the intrapopulation selfings in Fig. 5.10.

Repeated selfing, with the aim of developing pure lines, was started in Nigeria, Sumatra and Malaysia (Rosenquist, 1990), as well as the Congo. Initially, inbreeding depression was not noticed, but eventually the pure line strategy was abandoned. Apart from inbreeding depression, the main drawback is the time scale. Breeders of other crops regard eight generations of selfing as the minimum necessary to give near complete homozygosity. It would not be necessary to record each generation fully, so the total time could be less than the 60–70 years indicated by Table 5.6, but would still be several decades. Molecular markers might be used to select the most homozygous individuals, and thus to reduce the number of generations needed, or the need for inbreeding could be avoided completely by

the use of microspore culture (see Section 6.6.1.1), but the development of homogeneous clonal material has reduced the attraction of F1 hybrids.

It has been proposed that inbred lines might be used as planting material for oil palm, because genetic theory predicts that it should be possible to develop homozygous inbred progenies with yields equal or superior to the best heterozygous material (Jinks and Lawrence, 1983). The problem with this idea is that commercial planting material is heterozygous for the shell-thickness gene, for the very good reason that *teneras* yield 30% more oil than *duras*. Developing lines that are homozygous for all except one gene would not be a simple matter.

5.4.3 Inbreeding depression and heterosis

When self-pollination is done, or crosses between close relatives are made, the chance that the offspring may be homozygous for harmful recessive genes is increased. Inbreeding depression is essentially the decrease in vigour which results, and is commonly observed in cross-pollinated species. Heterosis is the opposite of inbreeding depression and can be defined as the superiority of the F1 cross over its better parent (Jinks and Lawrence, 1983).

Instances of inbreeding depression were noted at an early stage in oil palm breeding. Selfed *tenera* in Congo gave poor germination and irregular or deformed seedlings, while in Nigeria, comparisons between selfs and their crosses showed reduced cumulative yields in the selfs of 13–14% with Deli *duras* and 17–49% with other *duras* (5th Annu. Rep. NIFOR, 1969). Data from the Ivory Coast indicated strong inbreeding depression of yield with selfing within populations, although only interpopulation crosses were available for comparison (Gascon *et al.*, 1969). The occurrence of albino seedlings in some selfings has already been mentioned (Section 5.3.4.4).

The degree of inbreeding in a particular cross is measured by the inbreeding coefficient, F_x ; this is an estimate of the probability that both alleles of a particular gene are inherited from the same ancestor. F_x is 0 for completely out-bred palms, whose parents have no common ancestors; a single generation of selfing gives $F_x = 0.5$, a second generation $F_x = 0.75$, and so on, up to 1.0 for a completely homozygous inbred line.

In Malaysia, Hardon (1970) estimated the inbreeding coefficient for a range of Deli *dura* progenies, on the assumption that breeding from the original Bogor palms to the establishment of basic material in

Table 5.21 Correlations between progeny performance and inbreeding coefficient

Measurement	Correlation
FFB yield per healthy palm	−0.693***
Bunch number per healthy palm	−0.248
Mean bunch weight	−0.559**
Oil + kernel yield per healthy palm	−0.662***
Oil/bunch	−0.206
Fruit/bunch	−0.061
Mesocarp/fruit	−0.422*
Dry matter in mesocarp	0.221
Oil/dry mesocarp	−0.437*
Oil/wet mesocarp	−0.152
Kernel/fruit	−0.012
Shell/fruit	0.539**
Kernel/bunch	−0.074
Wilt index	0.160
Height	−0.710***
Trunk diameter	0.018
Leaf production rate	−0.196
Leaf area	−0.637***
Rachis length	−0.194
Leaf weight	−0.409*
Vegetative dry matter production	−0.606***
Leaf area ratio	0.112
Net assimilation rate	−0.374*
Bunch index	−0.463**

Data are from 30 crosses, based on the Yangambi programme (see Fig. 5.4), with F_x ranging from 0.03 to 0.75 (from Dumortier *et al.*, 1992).

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Malaysia was equivalent to three half-sib matings, giving an inbreeding coefficient of 0.305. Significant negative correlations between the coefficient and bunch yield were obtained, although this resulted from a strong negative correlation for mean bunch weight and a weak positive correlation for number of bunches. Estimates for the Yangambi programme also gave a negative correlation between yield and F_x . However, other data provided by Hardon and Ooi (1971) suggested that yield depression might not be significant where inbreeding coefficient was low (below about 0.3), particularly in the Deli *dura*, and that these low levels could be tolerated where considerations of adaptability of the material to the environment and the characteristics of the individual parents become overriding.

In a detailed study of the effects of inbreeding in Congo, Dumortier *et al.* (1992) calculated correlations between the inbreeding coefficient and a variety of yield components. Results are summarised in Table 5.21. The study confirmed Hardon's (1970) finding that

bunch weight is more affected than bunch number. Mesocarp/fruit was depressed and shell/fruit correspondingly increased, but the effect on oil/bunch was not significant. Height, leaf area and leaf weight were all depressed, but leaf production, rachis length and trunk diameter were not much affected. The results also gave some support to the idea that slight inbreeding does not matter: yield and height were not affected by F_x up to 0.14, but they were depressed at $F_x = 0.28$.

There have been instances of individual selfings showing little or no inbreeding depression. This has been taken as indicating that in such cases deleterious genes are largely absent; such palms were said to be 'tolerant of inbreeding' and might be expected to have good general combining ability (Rosenquist *et al.*, 1990). However, molecular marker studies have subsequently shown that one of the selfings highlighted by Rosenquist *et al.* (1990), 312/3 selfed, was in fact an illegitimate out-cross (Mayes, 1995), so it is uncertain whether this phenomenon of tolerance of inbreeding is a real one.

French workers extolled the value of 'interorigin' crosses for some years, but confined their evidence to comparisons involving Deli *dura* and African *pisifera* or *tenera* crosses (Gascon and de Berchoux, 1964). The performance of their interorigin crosses was attributed to the effect of a favourable combination of factors for weight per bunch and number of bunches from the parents (Gascon *et al.*, 1966). This is the additive yield component model already discussed in Section 5.3.2. The comparisons were not between selfed and out-crossed material, but of individuals from two populations, at least one of which was probably partially inbred. Thus, the benefits of the 'interorigin' cross were probably simply due to hybrid vigour.

5.4.4 Competition and planting density

It was recognised at NIFOR that palms differing in vegetative vigour may have different optimal planting densities. Table 5.22 shows that the mean optimal density for eight families was between 143 and 180 palms/ha, but two families yielded best at 273/ha, and the highest yield in the trial was obtained from progeny nine at that density (see also Section 9.3.5). Sparnaaij (1969) showed that during the first 4 years of production in Nigeria there was little interpalm competition, but that competition became a significant factor subsequently. In more favourable environments, competition affects yields earlier (Corley *et al.*, 1973a). At NIFOR, the four-row planting system was developed to try to take account of competition effects (Sparnaaij, 1969): by

Table 5.22 Progeny yields at four different planting densities

Progeny	Yield, years 10–17 (t/ha per year)			
	68 palms/ha	143 palms/ha	180 palms/ha	273 palms/ha
8	7.8	12.5	11.8	8.3
5	8.2	12.5	12.5	7.2
7	6.6	11.7	12.1	9.5
1	7.5	11.0	7.2	4.4
10	7.5	10.9	8.9	6.5
9	5.7	9.4	11.7	12.9
12	5.9	7.9	9.0	8.8
4	4.6	7.2	7.7	9.2
Mean	6.7	10.4	10.1	8.4

Data from NIFOR, quoted by Sparnaaij (1969).

planting four rows per progeny, and then omitting the fifth row, each progeny can be tested both at a conventional planting density (the inner rows), and under less than normal competition (the outer rows). Sparnaaij argued that the greater the yield difference between inner and outer rows, the lower would be the optimal density for the progeny, but this does not appear to have been confirmed. Okwuagwu (1989) presented a genetic analysis of two such trials, but did not consider whether the four-row system had shown useful differences in response to competition. As in earlier work, mean yields up to the fourth year of production were the same in inner and outer rows, but from the fifth year onwards the relative yield of the inner rows declined.

Hirsch (1980) found that yield of individual palms was positively (although not significantly) correlated with height. Yield of family plots, in contrast, showed a significant negative correlation with height. This was explained in terms of source limitation of total dry matter production, and consequent competition between vegetative growth and yield; this is essentially the overflow model discussed in Chapter 4. Nouy *et al.* (1990) showed that yield of inner and outer trees in a plot differed markedly when there was variation in height among the progenies. The discrepancy was positively correlated with height: outer trees in taller plots tended to benefit, and their yields could be more than 20% higher than inner trees. These results confirmed the hypothesis of Corley *et al.* (1971b) that, if selection is done under conditions of interpalm competition, the outcome may be competitive palms that fail to perform well when planted as a more uniform progeny or clonal population.

Corley (1973b) observed that the density giving maximum dry matter production was higher than that giving maximum yield. On the basis of this, Corley *et al.* (1971b) argued that yields could be increased by planting at higher density, and that palms with high bunch index (BI; see Chapter 4) would be best suited for high-density planting. Breure and Corley (1983) based selection on data from the early years of a planting density trial in PNG, when interpalms competition was minimal, and looked at the later performance, under competition, of palms selected for various attributes. They found that young palms selected for high early yield or for net assimilation rate tended to have above-average vegetative dry matter requirements and height increments, whereas those selected for BI did not show these faults, and they confirmed that palms with a high BI in the early years performed better later on than palms with high early yield. Table 5.16 shows that BI has a fairly low heritability, although comparable to that for yield of fruit. Direct selection for BI will best be based on family means rather than individual palms, therefore. In later studies in PNG, Breure (1985, 1986) showed that selection for high leaf area ratio, or for rapid ground coverage as measured by the rate of leaf area expansion, should lead to improved BI and yield. Smith *et al.* (1996) recommended that, in selecting clones suitable for high-density planting, material with very large leaf area or long rachises should be excluded, as should clones that achieved high yield through a large bunch weight, rather than large bunch number. They also considered that trials might need to be recorded for at least 12 years.

An alternative approach was proposed by Corley (1976a), who observed that many of the effects of high density were similar to those of severe pruning, and suggested that pruning might be used to identify progenies that would tolerate high-density planting. This suggestion does not appear to have been followed up.

The subject of optimal planting density, and the effects of competition on yield components, are discussed in more detail in Chapter 9.

5.4.5 Breeding and clonal propagation

The introduction of the $D \times P$ cross gave an immediate oil yield increase of about 30%, compared with the *dura* material which had been planted previously. The next big yield increase is expected to come from vegetative propagation. Research on this has been in progress for many years, as described in more detail in Chapter 6, but it has not yet reached the stage of large-scale commercialisation. Possible changes in breeding

methods resulting from the introduction of vegetative propagation are discussed below.

5.4.5.1 *Tenera* ortets

An obvious source of *tenera* ortets is $D \times P$ progeny trials, but as noted in Section 5.2.3, selection requires individual palm records, whereas for parent testing only bulk recording of plot yields would be needed. If breeding specifically for ortet production is contemplated, then $D \times T$ crosses have the advantage that both parents can be selected on phenotypic performance (Hardon *et al.*, 1987). Progeny testing of sterile *pisifera* parents would no longer be required, simplifying the breeding system, but clone testing would be needed, so no time would be saved. In addition, the lack of correlation for fruit composition between *dura* parents and *tenera* offspring might limit progress (see Section 5.3.3.1, *Dura and tenera shell thickness*). The efficiency with which individual palms can be selected as ortets depends on the broad sense heritability of the selection criteria. Tables 5.9 and 5.15 include some ortet-clone correlation data, indicating reasonable broad sense heritabilities for oil yield and its components. Selection methods for ortets are discussed in Section 6.4.1.

5.4.5.2 *Clonal seed*

As an alternative to clonal propagation of *tenera* ortets, with the attendant problems of commercial-scale tissue-culture work, propagation of the best *dura* and *pisifera* parents has been considered. A single *dura* parent palm will produce perhaps 10,000 seeds per year, so a small seed production unit, producing 2 million seeds per year, must have at least 200 *duras*; the Marihat Research Centre had 6500 seed parents in 1989 (Lubis *et al.*, 1990). The need for such numbers limits the selection intensity that can be applied; if the best few *duras* were to be cloned and the clones used as seed parents, a much higher intensity would be possible. With *pisiferas*, selection intensity can be very high without the need for cloning: a single *pisifera* may produce enough pollen for a production of 2 million seeds per year. However, clonal propagation could extend, in both time and space, the use that could be made of the best progeny-tested *pisiferas*. Breure (1998) imported clones of tested *pisiferas* to Indonesia from Costa Rica.

Veerappan *et al.* (2000) studied a number of 'semi-clonal' crosses, from clonal *duras* crossed with normal *pisiferas*, but unfortunately they only included a single comparison of two different plants of a clone crossed with the same *pisifera*. Such comparisons are needed to

confirm that clonal parents do breed true, as expected. A key question with clonal seed is the extent to which the abnormalities seen in clones (see Section 6.3) might be inherited. Rao and Donough (1990) showed that the mantled fruit abnormality was heritable, but palms showing this and other abnormalities could probably be excluded by selection within the *dura* clone.

Clonal seed would be a replacement for conventional seed, not for clones; it exploits the variation between families, but not that within families. Further progress would be possible by selecting and cloning the best *teneras* in the family. However, clonal seed should be appreciably cheaper to produce than clones (Section 6.5.3).

5.5 SELECTION AND BREEDING IN PRACTICE

5.5.1 Results of breeding work

Numerous papers have been published on the results of oil palm breeding trials. Some of these can best be described as advertising, their aim being to show that the authors have a breeding programme, and thus can be relied upon to produce good quality seed. A series of trials comparing seed from different producers has been organised by MPOB, but in published results the seed sources have been coded. Individual contributors will be told which code is theirs, so can compare their material with other, unidentified sources, but the only conclusion to be drawn by the general public is that sources differ. There is a large volume of useful published data, however, particularly in proceedings of the workshops and symposia organised by the International Society of Oil Palm Breeders. We shall not attempt to cover the whole field, but in this section will concentrate on results in a few important areas of oil palm breeding.

5.5.1.1 Progeny testing

The benefit to be obtained from *pisifera* progeny testing will depend on the amount of genetic variation within the *pisifera* population. Hardon *et al.* (1987) showed that the first generation of progeny testing of, predominantly, AVROS *pisiferas*, gave a yield increase of 12% (Table 5.23). They noted that *pisiferas* were normally taken for testing from T × T families already selected for superior performance of the *duras* and *teneras*; thus, the 12% improvement was additional to any benefit obtained from selection on family performance.

Table 5.23 Results of *pisifera* progeny testing: average performance of progenies from the best *pisifera* in each trial, as % of trial mean

Trial	<i>Pisiferas</i> tested	FFB yield	Oil/bunch	Oil yield
1	6	113	102	115
2	7	112	100	112
3	9	107	104	111
4	9	105	108	113
5	5	103	108	111
6	10	113	101	114
7	5	109	100	109
Mean		109	103	112

From Hardon *et al.* (1987).

The best *pisifera* of the 14 tested by Breure and Konimor (1992) had a breeding value 16% above the mean. All the *pisiferas* in this trial were AVROS or part AVROS. When a greater diversity of *pisiferas* is tested, the range found may be even greater: in a comparison of ten *pisiferas* of various origins, the best had a breeding value 26% above the mean (Rao and Corley, unpubl. data).

Progeny testing of *pisiferas* takes an additional generation, compared with the phenotypic selection done for *dura* parents. This is worthwhile if oil yield can be increased by 12% or more, but this is not always achieved. Lee and Yeow (1985) found, in three trials with AVROS material, that the best *pisifera* averaged only 6% above the mean. In the time that progeny testing would take, the original population could be improved by a further generation of selection. Lee (1999) compared two progeny-tested AVROS *pisiferas* with 24 untested *pisiferas* from the next generation, and found that offspring of the latter gave an average oil yield 8% greater. Progeny testing may be worthwhile, therefore, but it should not be done at the expense of further breeding.

In the course of testing *pisiferas*, a small sample of *duras* will also be progeny tested; the best of such *duras* can be selfed and used to 'reproduce' crosses (Section 5.5.2.3) or cloned for the production of clonal seed (Section 5.4.5.2).

5.5.1.2 Comparison of AVROS and other origins

As noted in Section 5.1.6.2, seed production in the Far East depends heavily on the AVROS population. This is because, in numerous comparisons, AVROS *pisiferas* have proved superior to other origins. Soh *et al.* (1981) compared pure AVROS T × T crosses with Dumpy-AVROS crosses, and found higher yields and better

Table 5.24 Breeding values for different *pisifera* origins in the Marihat programme

		Breeding values (adjusted least square means) for									
		FFB yield (kg/palm per year)		Bunch no. (no./palm per year)		Bunch wt (kg)		Oil yield (t/ha per year)		O/B (%)	Height incr. (cm/year)
Origin	Age (years):	4–6	7–9	4–6	7–9	4–6	7–9	4–6	7–9	4–9	
AVROS		191	199	20.9	11.4	9.4	18.1	5.73	6.24	23.2	76
Pure SP540		199	203	21.7	11.5	9.3	18.1	6.05	6.47	23.5	76
Yangambi		161	195	18.1	10.7	9.1	18.9	4.88	6.18	23.3	75
Marihat (ex-Cameroon)		153	175	16.8	9.8	9.3	18.5	4.37	5.25	22.3	74
Bah Jambi		173	186	19.1	10.3	9.2	18.6	5.04	5.66	22.6	83
Dolok Sinumbah		153	181	17.4	10.2	8.9	18.0	4.44	5.50	22.5	79
La Mé		184	211	21.4	12.4	8.8	17.6	5.31	6.37	22.3	70
Yocoboué		174	210	21.0	12.2	8.5	17.7	5.04	6.35	22.4	71

From Purba *et al.* (1995).

Table 5.25 Comparison of Ekona, Calabar and AVROS *pisiferas*

Material	F/B	WM/F	S/F	K/F	O/WM	O/B	Yield (% of AVROS)		Height (% of AVROS)
	(%)	(%)	(%)	(%)	(%)	(%)	FFB	O + K	
Deli × Ekona	68.7	85.9	9.4	4.7	48.7	28.7	100	102	82
Deli × Calabar	70.3	85.1	9.4	5.5	44.3	26.7	97	98	74
Deli × AVROS	69.3	84.3	8.7	7.0	45.2	26.4	100	100	100

From Sterling and Alvarado (1995); yields for first 3 years of production.
wm: wet mesocarp; for other abbreviations see Table 5.1.

bunch composition from the pure AVROS. Soh (1994) found superior BVs for FFB yield and oil/bunch for pure AVROS *pisiferas*, compared with Dumpy-AVROS. In Indonesia, Asmono *et al.* (1999) compared AVROS *pisiferas* with other Yangambi *pisiferas* descended predominantly from the Djongo palm. For FFB yield, averaged over five trials, the AVROS *pisiferas* (total of 23 crosses) outyielded the Yangambi *pisiferas* (33 crosses) by 6%. Purba *et al.* (1995) estimated breeding values for different origins in the Marihat programme. Some of their results are summarised in Table 5.24. They found that pure descendants of SP540 were slightly superior to AVROS for oil yield (AVROS is partly descended from a Bangun *pisifera* and from an illegitimate out-cross of SP540; see Section 5.1.1.3). In the early years of production, no other origin matched these. Hutomo and Pamin (1995) compared AVROS *pisiferas* with *pisiferas* from a repeat selfing of SP540 (AP73 1391 in Fig. 5.2), and found 3% greater FFB yield from the AVROS crosses.

Based on these comparisons, the exclusive use of AVROS *pisiferas* by seed producers appears justified,

but recent work shows that there are other origins with comparable performance to AVROS. In the study of Purba *et al.* (1995), although AVROS and SP540 were best in the early years, La Mé and Yocoboué gave comparable oil yields in years 7–9, with appreciably smaller annual height increment (Table 5.24).

Sterling and Alvarado (1995) compared AVROS with Ekona and Calabar *pisiferas*: in one trial, FFB yield from Deli × Calabar material was 97% of that from Deli × AVROS over the first 3 years of production, while in a second trial Deli × Ekona and Deli × AVROS gave equal yields over the same period. As Table 5.25 shows, both origins gave shorter trunks than AVROS, oil/bunch as good as or better than AVROS, and comparable yields of oil plus kernel. Rao *et al.* (1999) also compared AVROS and Ekona *pisiferas*, and presented results for eight contrasting pairs of *pisiferas* crossed with common *duras* from one trial, and ten pairs from a combination of two other trials. Results are summarised in Table 5.26, and show that the Ekona *pisiferas* gave FFB yields as good as or better than AVROS, together with comparable or better

Table 5.26 Comparison of Ekona and AVROS *pisiferas*

Origin	Trial	FFB (% mean)	B no. (% mean)	B wt (kg)	F/B (%)	WM/F (%)	O/WM (%)	O/B (%)	K/B (%)
Ekona	1, 2	99.5	99.2	6.7	60.2	84.5	45.9	23.3	3.6
AVROS	1, 2	99.5	90.9	7.3	63.1	82.2	42.4	21.9	5.3
Ekona	3	109.2	108.7	4.7	61.7	82.0	44.3	22.4	4.5
AVROS	3	88.5	80.1	5.2	65.2	83.1	42.0	22.7	5.4

From Rao *et al.* (1999).

wm: wet mesocarp; for other abbreviations see Table 5.1.

Table 5.27 Comparison of Deli × La Mé and Deli × Yangambi crosses

Location	Cross	Yield (kg/palm per year)	B no. (no./palm per year)	B wt (kg)	O/B (%)	O yield (t/ha per year)	Height ^a (m)	Rachis length (m)	Ref.
Sumatra, years 5–9	D × LM	214	18.9	11.6	24.2	6.47	–	–	1
	D × Ybi	204	17.3	12.4	24.3	6.20	–	–	
Sumatra, years 10–16	D × LM	218	10.6	21.3	24.2	6.60	5.8	–	1
	D × Ybi	198	8.6	23.6	24.2	6.00	6.6	–	
Malaysia, years 5–8	D × LM	178	20.2	9.1	23.5	5.74	0.48	5.8	2
	D × Ybi	175	18.8	9.6	25.4	6.14	0.55	6.1	
Malaysia, years 9–13	D × LM	157	–	–	25.1	5.83	0.61	–	3
	D × Ybi	172	–	–	27.5	7.00	0.64	–	
	D × NIFOR	155	–	–	26.7	6.12	0.65	–	
Malaysia, years 7–13	D × LM	172	–	–	25.3	6.44	0.50	–	3
	D × Ybi	172	–	–	27.0	6.87	0.54	–	
	D × NIFOR	162	–	–	25.9	6.21	0.55	–	

^aHeight increment for Refs. 2 and 3.

B: bunch; O: oil.

References: 1: Nouy *et al.* (1991); 2: Rajanaidu *et al.* (1986b) (data from three sites combined); 3: Chin (1992) (trials TW and VZ).

oil/bunch, but lower kernel/bunch. Breure *et al.* (2002) compared 15 AVROS *pisiferas* with five other *pisifera* origins (at least four palms per origin), and found that all five gave higher FFB yields than AVROS, but AVROS had the best mesocarp/fruit.

The AVROS population is narrowly based (although perhaps not so narrowly as the pedigree suggests, because of illegitimacy; see Section 5.1.1.3) and marker studies have shown a high degree of homozygosity in the material (Mayes *et al.*, 2000). There are likely to be advantages in widening the range of *pisiferas* in use, therefore, and introgression of Ekona and other origins with AVROS material should be worthwhile.

5.5.1.3 Comparison of La Mé and Yangambi

These two BPROs formed a key part of the RRS programme set up by IRHO in the 1960s. The

better drought tolerance of Deli × Yangambi crosses has already been mentioned (Section 5.3.6.1). However, in terms of yield, Deli × La Mé crosses were superior in Benin. Data from trials in North Sumatra and Malaysia are summarised in Table 5.27. There was not much difference in yield, although in Malaysia Deli × Yangambi had better oil/bunch and slightly higher oil yield, whereas in Sumatra oil/bunch did not differ, but Deli × La Mé had slightly higher FFB yield, particularly in older palms. Deli × La Mé had consistently higher bunch numbers and lower mean bunch weights than Deli × Yangambi. Interest in the Deli × Yangambi material has declined because of its greater vegetative vigour, as shown by greater height and rachis length in Table 5.27, and seed produced by CIRAD and its partners is now predominantly Deli × La Mé (Durand-Gasselin *et al.*, 2000a).

5.5.1.4 The Deli dura

Rosenquist (1986) suggested that the Deli *dura* should perhaps be considered as several different BPROs, because of the quite distinct paths of descent of different present-day populations. This view is supported by the results of comparisons made in Sumatra by Purba *et al.* (1995). Mean BVs for oil yield of different Deli populations ranged from 4.3 t/ha for RISPA to 5.1 t/ha for Dabou and Socfin; oil/bunch for *tenera* offspring ranged from 20.7 to 24.1% for the same origins. The range of BVs for the Deli populations was actually greater than the range for *teneras* for bunch weight and oil/bunch. Dumortier *et al.* (1992) found that Ulu Remis Deli had better BVs than Lofindi Deli for FFB and oil yield, but not for oil/bunch (Table 5.23).

Soh *et al.* (1981) compared Deli $\times$ *pisifera* crosses with Dumpy $\times$ *pisifera* (the Dumpy is a particular line of Deli *dura* material with reduced height; see Section 5.1.1.2). In one trial in Indonesia, the Dumpy crosses gave 18% less fruit, but with slightly better oil/bunch, and only 16% less oil. Asmono *et al.* (1999) found no differences between Deli $\times$ *pisifera* and Dumpy $\times$ *pisifera* crosses. 'Semi-Dumpy back-cross' *duras* gave D $\times$ P crosses with no differences from non-Dumpy D $\times$ P in yield or bunch composition. The semi-Dumpy crosses did have reduced height, but they also had the greater girth and larger leaves of the Dumpy. Soh *et al.* (1981) considered that the low yields and poor fruit/bunch seen in pure Dumpy material might be due to inbreeding (but note that fruit/bunch was not correlated with inbreeding coefficient in Table 5.21).

5.5.1.5 Fertile pisiferas

Attempts to develop pure fertile *pisifera* planting material started in Malaysia in the 1960s (Tang, 1971; Chin and Tang, 1979). Two Serdang fertile *pisiferas*, S112 and S29/36, were crossed, germination was satisfactory and 377 seedlings were successfully brought to bearing. The programme was expanded and continued, and the next generation of sib-crosses and crosses with unrelated *pisiferas* was described by Chin (1982, 1988, 1995). In some of the sib-crosses a large proportion of *teneras* was found; the average for 20 crosses was 17%, with a range from 0 to 43% (Chin, 1982). This appears to indicate contamination, though the out-crosses gave the expected 100% *pisiferas*.

In terms of yield, of 24 outcrosses, the best six had over 26% oil/bunch, compared with 21.3% for the D $\times$ P control, and oil yields per fertile palm between 43 and 61% better than the control. None of the

crosses was 100% fertile, with the proportion of 'fully fertile' palms ranging from 71 to 96%. If yields were expressed per planted palm, oil yields of the same six crosses were between 10 and 47% above the control. Based on these figures, there appears to be scope for further development of fertile *pisifera* planting material; clonal propagation of the best individuals should overcome the problem of partial sterility within progenies. However, one must consider whether it is worth the effort. Given that *teneras* can be found with no more than 5% shell, that the germination of *pisifera* seed is difficult (see Section 7.1.4.5) and, not least, that factory extraction equipment would have to be redesigned to handle shell-less fruit, it seems unlikely that fertile *pisiferas* will be the planting material of the future.

5.5.1.6 Interspecific hybrids

Hybrids between *E. oleifera* and *E. guineensis* have excited much interest among oil palm breeders. The morphology of these hybrids is discussed in Chapter 2; an important point is that although no *tenera* or *pisifera* *E. oleifera* palms have been found, the shell-thickness gene does operate in the hybrid. Crosses between *E. oleifera* and *pisifera* have thin shells, although they lack the fibre ring seen in *E. guineensis teneras*. The first trials were of *E. guineensis dura* $\times$ *E. oleifera* crosses, but most work has been done with *E. oleifera* $\times$ *E. guineensis pisifera* crosses, so yields can be compared with *E. guineensis teneras*.

The perceived advantages of interspecific hybrids are much slower height growth, a more liquid oil (Section 5.3.7.1), and resistance to fatal yellowing and marchitez sorpresiva (see Section 12.1.6.4). However, the hybrid also suffers from significant defects. Fruit set is often poor in the hybrids, as mentioned in Section 2.4, so that fruit/bunch is low, although a lack of fertile fruit may be compensated for by a high proportion of parthenocarpic fruit. Most seriously, the oil content of the mesocarp is also low: Hardon (1969) and Meunier and Boutin (1975) quoted oil/bunch figures of only 17–18%, compared with 22–23% with good *E. guineensis tenera* commercial material of the same era. Chin (1993) found that hybrids from Colombian *E. oleifera* gave poorer bunch quality than hybrids from the KLM palm (Section 5.1.7.3).

In a pilot milling exercise with hybrid fruit in Malaysia, Ismail *et al.* (1987) obtained only 2.8% factory oil extraction, but mentioned recording difficulties with a batch of only 49 t of fruit. Others have obtained much better extraction than this; Genty and Celis

Table 5.28 Summary of results of published genotype $\times$ environment studies

Reference	Locations	Significance of interactions			
		FFB	B no.	B wt	O/B
<i>(a) No significant interaction for yield</i>					
Rajanaidu <i>et al.</i> (1986b)	Malaysia $\times$ 3	ns	ns	ns	ns
Rajanaidu <i>et al.</i> (1986a)	Malaysia $\times$ 2	ns	—	—	ns
Chan <i>et al.</i> (1986): Trial 1	Malaysia $\times$ 2	ns	***	***	—
Trial 2	Malaysia $\times$ 2	ns	*	*	—
Trial 3	Malaysia $\times$ 2	ns	ns	ns	—
<i>(b) Significant interactions observed</i>					
Obisesan and Parimoo (1985)	Malaysia $\times$?	*	*	—	—
Chan <i>et al.</i> (1986): Trial 4	Malaysia $\times$ 2	**	***	***	—
Ong <i>et al.</i> (1986)	Malaysia $\times$ 4	***	***	***	***
Rajanaidu <i>et al.</i> (1992)	Malaysia $\times$ 5	*	**	**	—
Rajanaidu <i>et al.</i> (1993): Trial 1	Malaysia $\times$ 6	*	*	*	ns
Trial 2	Malaysia $\times$ 3	**	*	ns	—
Yong <i>et al.</i> (1993)	Malaysia $\times$ 5	***	***	***	—
Yong and Chan (1990)	Malaysia $\times$ 2	**	ns	**	—
Lee <i>et al.</i> (1988)	Malaysia $\times$ 2	**	**	**	**
<i>(c) Studies with oil palm clones</i>					
Lee and Donough (1993): Trial 1	Malaysia $\times$ 3	**	**	**	ns
Trial 2	Malaysia $\times$ 3	**	**	ns	*
Corley <i>et al.</i> (1995b)	Malaysia/Sumatra	ns	**	ns	—

From Corley *et al.* (1993), updated.

B: bunch; O: oil.

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$; ns: not significant; —: not tested.

(1997) quoted 16%, and M. Herrera (pers. comm., 1997) obtained an average factory extraction of 18.6% from four batches of fruit in Colombia. Genty and Celis (1997) also noted that fruit detachment and build-up of free fatty acids (FFA) were slow, so that harvesting rounds might be extended compared with *E. guineensis*. Sambanthamurthi *et al.* (1995) found much lower lipase activity in *E. oleifera* mesocarp, which could explain the slow development of FFA.

To try to improve oil yield, without losing the advantages of the hybrid, programmes of back-crossing the hybrid to *E. guineensis* have been undertaken (Obasola *et al.*, 1977; Tam *et al.*, 1977; Sterling *et al.*, 1988; Sharma and Tan, 1990; Le Guen *et al.*, 1993; Chin, 1993; Oboh, 1993; Din and Rajanaidu, 2000). Back-crosses are generally described as highly heterogeneous; fruit set and oil/bunch may be improved, and the reduced height of the hybrids may be inherited, but oil composition is close to that of *E. guineensis* (see Table 5.18). The obvious approach is to clone the best individuals from back-crosses (Malaurie, 1987; Ho, 1999), but no data for individual palms have been published, so it is not possible to judge what might be achieved by this.

5.5.1.7 Genotype $\times$ environment interactions

For many years it was thought that $G \times E$ interactions were not very important in the oil palm; Rosenquist (1982) found highly significant correlations between yields of the same progenies in Malaysia and in PNG, indicating that there was little $G \times E$ effect. Several other authors found no significant interactions for yield of fruit (Table 5.28a). In most studies, though, either the progenies were similar in origin, or the environments compared were actually very similar. The lack of interaction was therefore not entirely surprising. In more recent work, with more diverse genotypes or environments, significant interactions have been observed (Table 5.28b). With the development of clonal material, such interactions are likely to become increasingly important (Table 5.28c). The table shows that, in contrast to yield of fruit and its components, interactions for oil/bunch are unusual.

There is a variety of reasons for $G \times E$ interactions. Azman *et al.* (1998) and Kushairi *et al.* (2001) observed significant interactions, between progenies and fertiliser levels, as did Donough *et al.* (1996b) between clones and fertilisers; thus, interactions with inherent

soil fertility might also be expected. Differences in disease incidence can be a factor (Corley *et al.*, 1993). These authors compared the same progenies planted in Malaysia, Congo and Cameroon, and suggested that material with high mean bunch weight yielded less well in poor environments than high bunch number families. Clone $\times$ density interactions are also important (Corley and Donough, 1992).

In annual crops, where much environmental variation consists of year-to-year differences in the weather, breeders have selected for broad adaptability, giving yield stability across a range of years and conditions. For a perennial crop, which once established will remain for many years, it may be more productive to look for specific adaptations, exploiting $G \times E$ effects to maximise yield in each different environment, and there is little doubt that much work on clone $\times$ environment interactions will be needed in future.

5.5.2 Progress achieved through breeding

Measuring breeding progress is difficult. Yields are much higher now than they were in the early days of the oil palm industry: Lee and Toh (1991) quoted yields from breeding trials planted in 1962 of 4.9 t oil/ha per year (22.6 t FFB with 21.8% O/B), increasing to 8.7 t/ha from 1979 plantings (33.7 t FFB with 25.8% O/B), but part of this increase was undoubtedly due to changes in agronomic practice. Davidson (1993) showed that plantation-scale yields in one company in Malaysia had increased from 1.3 t oil/ha in 1950 to 5.4 t/ha in 1990; after a detailed analysis, he attributed about half of this to breeding and half to agronomy and milling efficiency. Separating the effect of breeding progress from other factors is difficult, but there are two sets of data where a distinction can be made. The first data set comes from a trial planted in Malaysia in 1970, in which current Deli *dura* material was compared, in the same trial and under the same agronomic conditions, with palms from seed collected in some of the earliest plantings from the nineteenth and early twentieth centuries. Davidson (1993) used the results of this trial (Section 5.5.2.2) in his analysis.

The second source of information is the IRHO/CIRAD programme (Section 5.5.2.3). Most trials in this programme have included the same standard cross, L2T $\times$ D10D, so progress can be evaluated by comparison with a constant standard. These two palms, planted in the 1920s, were still alive in 2001, and still being used to produce seed for trials (T. Durand-Gassel, pers. comm., 2001). Jacquemard *et al.* (1982)

showed that crosses between selfings of the palms gave very similar performance to the original cross, so these could be used as a substitute standard when necessary.

Both of these programmes are discussed below. First, though, the theory of expected selection progress is briefly discussed.

5.5.2.1 Theoretical selection progress

The progress expected from selection can be estimated quite simply. It depends on the amount of variation present in the starting population, on the intensity of selection (the fraction of the population which is selected) and on the heritability of the character. As noted in Section 5.2.6.2, heritability is the probability that offspring will inherit a particular character from their parents. The equation for expected response to selection (R , in the same units as the character under selection) is:

$$R = i h_n^2 SD \quad (5.9)$$

where h_n^2 is the narrow sense heritability, SD is the standard deviation of the character under selection in the starting population, and i is a measure of selection intensity. If the selection response is expressed as a percentage of the population mean, then SD can be replaced by the coefficient of variation (CV), and R is then a percentage of the mean. Falconer (1981) gave tables with values of i , which is in standard deviation units, for different selection intensities.

As an example, consider a population with a CV for oil yield of 20% and a heritability of 0.25 (Section 5.3.3.2). If the best 5% are selected, $i = 2.06$ and $R = 10.3\%$. For 1% selection, $i = 2.66$ and $R = 13.3\%$. Note that i is not directly proportional to the actual fraction selected, but is derived from a normal distribution; a large increase in selection intensity gives a relatively small change in i and thus in R .

This theoretical derivation of expected selection progress has been used to compare different selection schemes. Soh (1986), in a study of the progress to be expected from clonal propagation, used broad sense instead of narrow sense heritability (because a clone will carry all the genetic characteristics of its parent, not only those that are additively inherited). He concluded that combined family and individual selection would be more effective than either family or individual selection alone, and that progress of 8–16% might be obtained from the particular $D \times P$ population that he studied. Other populations, with greater or lesser CV s, would give different results; heritability also depends on the population, on the environment in which it is tested and on the precision of the measurements (Section 5.2.6.2).

Table 5.29 Yield, vegetative measurements and dry matter production of Deli *dura* palms before selection, and after one or four generations of selection

Generations of selection: Population:	0 Bogor	0 T. Morawa	1 Elmina	4 Modern
Yield of fruit (kg/palm per year)	121.3	112.0	144.2	181.5
Bunch number (no./palm per year)	12.9	10.8	12.6	16.0
Mean bunch weight (kg)	9.4	10.4	11.5	11.4
Mesocarp/fruit (%)	59.7	61.0	58.5	64.0
Kernel/fruit (%)	9.9	9.7	9.2	7.9
Shell/fruit (%)	30.4	29.3	32.2	28.0
Oil/bunch (%)	17.3	18.5	17.2	18.4
Oil yield (kg/palm per year)	21.0	20.7	24.8	33.4
Trunk height (m, 18 years old)		6.5	8.0	7.5
Mean leaf area (m ²)		9.8	9.1	9.2
Dry matter production (kg/palm per year)	172		190	201
Vegetative dry matter (kg/palm per year)	108		110	100
Bunch index (%)	37.3		41.9	50.7
Estimated light interception (%)	85		87	80
Energy conversion (e, g dry matter/MJ)	1.05		1.14	1.36

From Lee *et al.* (1990) and Corley and Lee (1992); for some data, the two unselected populations were combined.

5.5.2.2 Progress in the Deli *dura* population

Selection progress in the Deli *dura* population up to the late 1960s was evaluated in a trial in Malaysia (Lee *et al.*, 1990; Corley and Lee, 1992). In 1968, J.J. Hardon collected random samples of seeds from:

- the 13 palms remaining in the 1878 Bogor Economic Garden at that time;
- 30 surviving palms in an ornamental avenue at Tanjong Morawa estate, planted between 1888 and 1895, and probably unselected second or third generation descendants of the original Bogor palms (see Fig. 5.1);
- an old commercial field on Elmina estate in Malaysia, planted in about 1927;
- Deli *dura* progenies in the third or fourth generation of a breeding programme derived from the Ulu Remis population (see Fig. 5.1).

It was assumed that the Economic Garden and Tanjong Morawa palms were unselected, and that the Elmina planting was the result of one generation of selection; the modern material had undergone about four generations of selection. A trial was planted with these materials in 1970; results are summarised in Table 5.29.

Yield of fruit was increased by 50% from the unselected to the fourth generation material, with improvements in both bunch number and mean bunch weight. Oil/bunch was slightly increased, mainly

through improved mesocarp/fruit; changes in other bunch components were small, but the increase in mesocarp/fruit appeared to be at the expense of both kernel and shell. In terms of vegetative vigour, after one generation of selection, the palms were taller, but after four generations this was starting to be reversed, perhaps because by the late 1960s breeders were starting to take account of vegetative growth in selection. It appears that oil palm breeders have improved the photosynthetic light conversion efficiency (*e*), leading to higher dry matter production. As vegetative dry matter production per palm remained fairly constant, the overflow model predicts that this should lead to higher yield (see Chapter 4).

Hardon *et al.* (1987) estimated that selection progress in the second and subsequent generations was about 10–15% per generation. With a generation time of 10 years, this is equivalent to at least 1% per year. To the 60% increase in oil yield of the Deli *dura* shown by this study, Davidson (1993) added a further 30% from the introduction of the D × P cross, the first plantings of which in Malaysia were made in the late 1950s.

Some authors have suggested that phenotypic selection is not effective in the oil palm, but the progress described here was the result of phenotypic selection. However, Hardon *et al.* (1987) found that phenotypic selection in modern Deli *dura* material was no longer very effective. The best families in 14 sets of D × P crosses from single *pisiferas* outyielded the mean for the

Table 5.30 Estimates of breeding progress in the IRHO/CIRAD programme. The basis for these estimates is explained in the text

Stage of programme	Location	Oil yield (t/ha per year)	Yield as %		Source of data
			Std cross	Base pop.	
Base population	La Mé	2.81	93	100	1, 2
Selected crosses after 1st cycle	La Mé	3.32	109	118	3
Second cycle crosses	La Mé	4.52			
	Indonesia	6.71	118	127	3
Best 2nd cycle crosses	Indonesia		122	131	3

References: 1: Le Guen *et al.* (1989); 2: Nouy *et al.* (1991); 3: Gascon *et al.* (1981).

pisifera by 7%, but phenotypic selection of *duras* did not identify the best, and only gave a 3% yield improvement. This perhaps reflects the lack of additive variation remaining in the Ulu Renis Deli *dura* population (Hardon and Thomas, 1968; Ooi *et al.*, 1973).

5.5.2.3 Progress in the CIRAD programme

The development of this programme is described by Durand Gasselin *et al.* (2000a). Following the *Experience Internationale* in the 1950s (Section 5.1.3.1), the RRS scheme was introduced. In the 1960s, 529 test crosses between Deli *duras* (defined as group A) and African *teneras* (La Mé, Yangambi, NIFOR; group B) were planted. Of these, 15 were selected for release as commercial seed (Gascon *et al.*, 1981). The average yield of these 15 crosses was 18% above the mean of all crosses. The standard cross, L2T × D10D, was one of those selected at this stage, and was apparently about 8% better than the overall mean for all crosses (from data in Le Guen *et al.*, 1989; Nouy *et al.*, 1991).

Jacquemard *et al.* (1982) demonstrated that a mixture of crosses between the selfs of two parent palms gave the same yield as the original cross between the parents, and estimated that 12–20 families were needed to give a yield within 5% of that of the original cross, with 95% confidence. They also showed that selection of *duras* within the selfing for mesocarp/fruit and height could enhance the performance of the reproduced cross; for height, a 5% reduction in annual increment could be achieved by selecting the shorter 50% of parents.

A second cycle of test crosses was started in 1975, and nearly 500 ha of trials were planted in Africa and Indonesia. Gascon *et al.* (1988) showed that the yields of these second cycle crosses were 36% better than those from the first cycle, but changes in agronomic factors were not excluded from this figure. If yields are

compared with those of the standard cross, the best second cycle crosses showed an improvement of 22%; given that the standard cross was 8% better than the original population, this indicates overall progress of 31% (Table 5.30), equivalent to about 1% per year.

According to Durand-Gasselin *et al.* (2000a) yields had been increased by 42% between 1960 and 2000. The exact basis for this estimate was not explained, but it is, again, equivalent to about 1% per year. In addition to this progress in yield, palm height has been reduced (Jacquemard *et al.*, 1997) and resistance to *Fusarium* wilt has been greatly improved (de Franqueville and Renard, 1990; Durand-Gasselin *et al.*, 2000b).

Meunier *et al.* (1989) showed that, in the CIRAD programme, yield increases had come predominantly from increases in bunch number (and oil/bunch), and not from mean bunch weight. In the Deli *dura* (see Table 5.29), both number and weight have been increased, but the increase in number is greater (35% compared with 15%).

5.5.2.4 Conclusion

Both of these studies indicate breeding progress of at least 10% per decade. On this basis, therefore, there seems little to choose between RRS, in the CIRAD programme, and FIS with the Deli *dura*. Reverting to Equation 5.9, what determines breeding progress is not so much the breeding scheme adopted, but the selection intensity applied, and the variation available to the breeder.

5.6 OIL PALM IMPROVEMENT IN THE FUTURE

It is clear that good progress has been made in the past by oil palm breeders; the best yields in breeding trials

Table 5.31 Yields from best individual families in breeding trials

Location	Years	FFB yield (t/ha per year)	O/B (%)	K/B (%)	Oil yield (t/ha per year)	Kernel (t/ha per year)	PKO	Total oil	Ref.
Malaysia	Years 3–10	33.6	27.9	7.0	9.4	2.4	1.2	10.6	1
Malaysia	5 years	38.4	28.1	4.4	10.8	1.7	0.8	11.6	2
PNG	Years 4–7	29.8	35.4	3.8	10.5	1.1	0.5	11.0	3
Malaysia	Year 10	40.0	27.2	5.0	10.9	2.0	1.0	11.9	4

O: oil; B: bunch; K: kernel; PKO: palm kernel oil, assumed 50% of kernel yield.

References: 1: Lee and Toh (1991); 2: Sharma and Tan (1997); 3: Dumortier and Konimor (1999); 4: Soh A.C. (best clone; pers. comm., 2002).

have exceeded 10 t oil/ha/per year as shown in Table 5.31. Despite this evidence for past success, though, Tinker, in a review in 2000, noted that average yields in Malaysia appeared to have stagnated, and asked whether breeding was still making progress (Tinker, 2000a). We believe the main problem is the inability of plantations to exploit fully the genetic potential of the material. However, there are some factors suggesting that breeding progress may be slowing. Restriction of commercial planting to Deli $\times$ AVROS crosses in many programmes is undoubtedly starting to impose limitations. It has been shown that in some Deli populations there is little additive variation in yield remaining (see Sections 5.1.6 and 5.1.7.5) and further selection progress in the AVROS population seems to be proving difficult (Dumortier, 1999). Up to now, breeders have neglected much of the gene pool, as noted by Hardon and Corley (2000), and the introduction of new material to increase variability should remain a priority for all oil palm breeding programmes.

The main objective of oil palm breeding has been, and will probably continue to be, increased yield. Estimates by Corley (1983b, 1998) suggested potential oil yields per hectare of about 18 t, based on observed maximum values for the various growth and yield components. An oil/bunch as high as 50% may be possible, with 80% fruit/bunch, 95% mesocarp/fruit and 65% oil/fresh mesocarp, combined with a bunch production of around 37 t/ha. Higher bunch yields have

already been achieved (e.g. Table 5.31), but only with much lower oil/bunch. The high energy content of oil, combined with source limitation of yield (see Chapter 4) means that, if oil/bunch is increased, with other things being equal the weight of bunches will decrease (Corley, 1973a).

Some other breeding objectives have been discussed in Sections 5.3 and 5.4. Further possibilities include longer bunch stalks for ease of harvesting (Le Guen *et al.*, 1990) and non-shedding fruit, to maximise oil/bunch without the need for loose fruit collection (Donough *et al.*, 1995).

The next major developments in oil palm planting material will involve clones, clonal seed and genetic engineering. Cloning the best *dura* parents to produce clonal seed would allow a much higher selection intensity to be applied (Section 5.4.5.2). Currently, up to 25% of *duras* may be selected as seed parents in some programmes. Equation 5.9 predicts that, if this were reduced to the best 1%, selection progress would be doubled (for 25%, $i = 1.25$; for 1%, $i = 2.66$).

Commercial planting of *tenera* clones should give a further yield increase but, as discussed in Chapter 6, there have been problems with large-scale propagation, and commercial planting of clones is only just starting. At present, genetic engineering is being discussed in relation to the production of speciality oils, but there are also possibilities for increasing yields.

Chapter 6

Vegetative Propagation and Biotechnology

In a cross-pollinating crop such as the oil palm, progenies will be genetically heterogeneous if reproduction is by way of seed, and the potential yield for each plant will be different. If it were possible to produce genetically uniform plants, and if these were of superior genotypes, considerable yield increases would be possible. With some crops, pure lines are produced by inbreeding, and these are crossed to produce hybrid seed, but this has not been done with oil palm because of the time needed to produce pure lines (Section 5.4.2.5, but see also Section 6.6.1.1).

In many perennial crops genetically uniform material can be produced by vegetative propagation, using suckers, cuttings or grafts, where the genetic constitution of all 'offspring' is identical with that of the original material. All individual plants with the same genetic composition, produced from the same original material in such ways, are collectively called a clone. The members of a clone are known individually as 'ramets'. With such techniques selected genotypes can be readily reproduced for commercial use. The greatest benefit of clonal propagation will be the yield increases possible; the resulting uniformity might also simplify management of harvesting and other aspects, although it may also have disadvantages where characteristics such as disease susceptibility are involved.

The oil palm only has a single growing point, and does not produce suckers like some other palm species, so clones cannot be produced by the common techniques referred to above. However, it is possible to produce clones by tissue culture, in which small pieces of tissue (explants) are grown on special nutrient solutions. The plant from which the tissue is taken is known as an ortet. The growing tissue may form callus (a mass of cells without differentiation), and this may be treated to produce embryoid tissue, that slowly grows into plant shoots. These can be rooted and planted in a nursery, and thereafter handled in much the same way as ordinary seedlings. The tissue-culture techniques are difficult and laborious, and the underlying biology is not properly understood, so that finding successful methods is very slow.

Apart from propagation by tissue culture, the other aspect of biotechnology included in this chapter is genetic engineering, or DNA transformation. The third area, where biotechnology is already making a significant contribution, is that of molecular markers. That subject is covered in Section 5.2.8.

6.1 HISTORY OF OIL PALM TISSUE CULTURE

Attempts to propagate oil palm by tissue culture started in the 1960s, and by the mid-1970s success had been achieved (Jones, 1974; Rabechault and Martin, 1976). The early work was reviewed by Jones (1995) and Corley (1993). The first clonal palms were planted in the field in Malaysia in 1977 (Plate VIII B) and the first replicated trials in 1978 (Corley *et al.*, 1979). Following this success, there was a rapid expansion of effort, and by the mid-1980s, there were at least ten laboratories in Malaysia doing oil palm tissue culture (Wooi, 1990) and several others elsewhere (Le Guen *et al.*, 1991). The discovery of abnormal flowering and severe bunch failure caused a major setback, just as commercial exploitation was about to begin (Corley *et al.*, 1986). Since the 1980s, there has been a great deal of research on the abnormal flowering problem, and by the late 1990s there was cautious expansion into commercial planting of clones.

6.2 TISSUE CULTURE METHODS

6.2.1 Culture on solid media

Propagation of oil palm by tissue culture, sometimes known as micropropagation, involves placing micro-biologically sterile tissue samples on a culture medium, solidified with agar and containing mineral nutrients, sugar and vitamins, to stimulate the formation of a callus tissue with auxin-type growth regulators. Somatic embryogenesis, the formation of embryo-like bodies on the callus, is then induced, the embryoids develop

Box 6.1 The tissue culture propagation process: time scales and success rates

1. Sampling		2000 leaf explants can be set up from one sampling
2. Callus initiation	1–15 months	All palms sampled usually give some callus. Between 2% and 60% of leaf explants from an individual palm may develop callus (average 19%)
3. Embryogenesis	5 months to 3 years	80–90% of palms eventually give embryoids, but only on a small proportion of callus cultures (average 4%)
4. Proliferation	6 months or more	Only about 40–50% of embryoid cultures proliferate freely
5. Shoot development		This occurs simultaneously with proliferation
6. Rooting	2–4 months	Usually more than 80% within 2 months, and over 90% after 4 months, but some clones prove difficult to root
7. Hardening, transplanting		More than 90% survival is usual

Based on Wong *et al.* (1999b), Duval *et al.* (1995a) and Rival *et al.* (1997) and Rival (2000).

shoots, and are rooted, hardened off and transplanted to the nursery. Repeated subdivision and further growth at the callus or the embryoid stage increases the number of cultures from the original tissue sample, giving the multiplication necessary for a propagation system. The process that has become more or less standard is outlined in Box 6.1 (also Plate VII). However, the large number of variables in the culture process has meant that different laboratories often obtain different results from superficially similar treatments, and even in the same laboratory results are not always repeatable, so there remains some uncertainty as to the best procedures.

For a long time, very few details of methods and culture media were published, but Paranjothy and Rohani (1982), Nwankwo and Krikorian (1983) and Teixeira *et al.* (1993) described their methods, and Paranjothy (1986) and Wooi (1995) summarised published information. The basic culture medium is almost always the MS formulation of Murashige and Skoog (1962), with the Y3 medium of Eeuwens (1976) also sometimes used. Callus cultures are usually kept in darkness; embryoid cultures and plantlets are kept under light from fluorescent tubes.

6.2.1.1 Tissue sampling and callus formation

The tissue samples (explants) most commonly used are immature leaf or inflorescence, or the tips of tertiary roots. Roots are always heavily contaminated with soil fungi and bacteria, and need vigorous disinfection; Wooi *et al.* (1981) recommended 0.1% mercuric chloride followed by 10% sodium hypochlorite. There is also a danger of taking, in error, roots from an adjoining palm (Kerslake, 1984; Mayes *et al.*, 1995, 1996). To avoid this problem, soil can be mounded up around the palm base and roots growing into it can be sampled, but even

then care must be taken to exclude roots from neighbouring palms growing into the mound from below, and roots of seedlings that may have germinated in leaf axils above the mound.

Using leaf explants avoids any risk of error, and young leaf tissue does not require severe disinfection, being completely enclosed by the bases of older leaves. The tissue must be immature, though; the bases of unopened leaves are used (Noiret *et al.*, 1985) and excision causes a severe check to the palm's growth, with a risk of death. Sampling (Plate VIIIA) cannot be done more frequently than every second or third year, and palms in use for a breeding programme cannot be sampled. Lim L.L. *et al.* (1999) found no differences in frequency of callusing between leaves –1 to –7. Young inflorescence tissues from the axil of about leaf 10 give good results, and can be excised without damaging the palm too seriously (Wooi *et al.*, 1981; Teixeira *et al.*, 1994), but general experience appears to be that callus initiation and embryogenesis occur sooner with leaf explants than with inflorescence (C.J. Eeuwens, pers. comm., 2001).

Wooi (1995) found no difference in callus frequency from root explants between palms aged 9–10, 14–16 and 22–23 years, but Paranjothy *et al.* (1990) found that young palms (3 years old) gave significantly higher callus frequencies than 10-year-old palms, from both leaf and root explants. However, the need for recording over several years to identify the best individuals means that sampling cannot usefully be done from 3-year-old palms.

An auxin, usually 2,4-dichlorophenoxyacetic acid (2,4-D) or α -naphthalene acetic acid (NAA), is essential for callus initiation, but cytokinins are inhibitory (Paranjothy *et al.*, 1990). Callus may be initiated within 2 months of putting explants into culture. Most callus grows slowly, forming a compact, nodular mass

(Plate VIIA), but a fast-growing callus may develop spontaneously (Smith and Thomas, 1973) and can be induced on suitable media (Duval *et al.*, 1995c). Embryogenesis occurs readily on fast-growing callus, but it appears that the embryoids are more likely to suffer from the flowering abnormality (Section 6.3), so slow-growing, nodular callus is preferred (Duval *et al.*, 1988). Using leaf explants, all palms sampled give callus, with the proportion of mature palm explants giving callus ranging from 7 to 60% (Wong *et al.*, 1999b; Rival, 2000). Ortets of Deli $\times$ La Mé origin gave higher callus frequency than Deli $\times$ Yangambi or Deli $\times$ NIFOR (Rival, 2000). From 18-month-old seedlings, 52% of explants gave callus (Wong *et al.*, 1999b).

6.2.1.2 Embryogenesis and embryoid proliferation

The formation of embryoids on callus (Plate VIIB) is stimulated by transferring to a medium with reduced auxin concentration (Paranjothy and Rohani, 1982; Nwankwo and Krikorian, 1983). Embryoids may also occasionally form directly on leaf explants, without a visible intervening callus stage (Wooi, 1990). However, the interval between callus initiation and embryogenesis is unpredictable and success is not guaranteed: typically, embryoids are only obtained from about 85% of palms put into culture (see Box 6.1) (Wong *et al.*, 1999b; Rival, 2000).

The multiplication necessary for a propagation system is achieved by embryoid proliferation. This involves subdividing the cluster of embryoids from a well-developed old culture and inoculating several tubes of fresh proliferation medium, while transferring any shoots to rooting medium. The proliferation medium may be hormone free (Rival, 2000) or with auxin only, or auxin and cytokinin (Paranjothy *et al.*, 1995a). Only about 50% of embryoid 'lines' proliferate (Wong *et al.*, 1999b; Rival, 2000); the reasons for the lack of proliferation with other lines are unknown. An embryoid line consists of all the embryoids descended by proliferation from a single embryogenic event in a callus culture.

In most laboratories, the number of subcultures per embryoid line is deliberately restricted, because of the possibility that the flowering abnormality may be related to time in culture (Section 6.3.1.1). If this is done, then for large-scale propagation several lines per palm are needed, but Soh *et al.* (2001) reported that less than 20% of palms sampled gave more than ten proliferating embryoid lines (although clearly this must depend on the number of callus cultures established). Rival (2000) described this as the main stumbling block for large-scale

clonal propagation. Wong *et al.* (1997) showed that proliferation was encouraged by shorter intervals between transfers to fresh culture medium, but Jones (1995) noted that short transfer intervals tended to increase the frequency of abnormal flowering (see also Section 6.3.1.2).

6.2.1.3 Shoot development and rooting

Development of shoots (Plate VIIC) occurs, simultaneously with further proliferation of other embryoids in the same culture, on a hormone-free medium (Rival, 2000), or one with a low cytokinin concentration (Paranjothy and Rohani, 1982). At each subculture, shoots are separated from embryoids and transferred to a rooting medium, while the embryoids are recycled. According to Wooi (1990), root development can be stimulated by transfer to a medium with very low NAA concentration, or by a short exposure to high NAA, followed by hormone-free basal medium. Rival *et al.* (1997) placed shoots in a medium with 1 mg/l NAA for 24 h, then transferred to a hormone-free medium, but Rival (2000) stated that 8 weeks on a medium with 0.5–1.0 mg/l NAA was the preferred method.

6.2.1.4 Hardening and transplanting

Once a good root system has formed in culture, the ramet can be transferred to a prenursery or to sand beds (Plate VIIE). Plants in culture do not form a normal leaf cuticle, so are very rapidly desiccated when exposed to dry air. Thus, it is necessary to maintain high humidity in the first nursery stage, until the plants are well established, and to avoid high temperatures. In practice, this is achieved with polythene tunnels or mist spraying, and suitable shade netting (Wuidart and Konan, 1989; Tan *et al.*, 1999). Wooi *et al.* (1981) tested antitranspirant sprays, but found that enclosure under polythene sheet was much more successful.

Initial survival may be better in sterile soil than in non-sterile, but without mycorrhizal infection in sterile soil growth is very slow and symptoms of phosphate deficiency develop. Inoculation with mycorrhizal spores, or addition of a small proportion of non-sterile soil, can overcome this problem (Blal and Gianinazzi-Pearson, 1990; Corley, 1993) but, with care, even in non-sterile soil survival rates of over 95% can be achieved. Schultz *et al.* (1998) found that mycorrhizal inoculation improved survival.

Growth of ramets in the nursery is initially slower than that of seedling palms, because the latter have the kernel food reserve, but after about 12 weeks, growth rates of clonal plants and of seedlings are comparable (Wooi *et al.*, 1981).

6.2.1.5 Conclusions

Tissue culture is now widely used for propagation of oil palms on an experimental scale. However, it is still not possible, after 30 years of work, to propagate any palm to order. Embryoids can be obtained from 80–90% of ortets, but proliferation to give the numbers of plants necessary for clone testing, and ultimately for commercial planting, still presents problems, with less than 50% success.

6.2.2 Storage of oil palm cultures

Clone testing takes 7 or 8 years. During that time, the clones must be maintained in some way, so that after testing the best can be propagated commercially. The simplest approach is to use the clones in the trial itself as a 'store', which can be sampled for further culture when required, but because of concerns about possible risks of recycling through culture (Section 6.5.2), two other approaches have been investigated.

6.2.2.1 Cryopreservation

Grout *et al.* (1983) showed that it was possible to revive and germinate oil palm zygotic embryos (embryos from seeds) after freezing in liquid nitrogen. The very low temperature of liquid nitrogen (-196°C) more or less stops all biochemical processes, making it very unlikely that any genetic changes will occur during storage. Engelmann and Duval (1986) found that small, white, 'finger-shaped' embryoids, formed after culture on a medium with high sucrose content, survived freezing in liquid nitrogen. Not all clones produced the type of embryoid required, however, and success rates were rather low, with only about 20% of cultures resuming growth after thawing. Dumet *et al.* (1993a) showed that, by introducing a desiccation stage, drying the embryoids to between 19 and 35% moisture content, a proportion of any type of embryoids would survive freezing, although success rates were still variable. Storage at -80°C was as good as -196°C for desiccated embryoids, but survival at -12°C was poor (Dumet *et al.*, 1994a). Pregrowth on sucrose was shown to reduce the water content of embryoids (Dumet *et al.*, 1993b), but for good survival it was necessary to dry the embryoids further, to a point where ice crystals no longer formed in the cells during freezing. Pregrowth with sucrose was more effective than with other sugars (Dumet *et al.*, 1994b).

6.2.2.2 Storage with minimal growth

A cheap alternative to cryopreservation is storage under conditions allowing little or no growth. Engelmann

(1990) showed that the interval between transfers to fresh medium could be extended to 4 months for cultures under 1% oxygen. Cultures maintained at 15°C , instead of the usual $25\text{--}30^{\circ}\text{C}$, could be kept for 6–9 months without transfer (Paranjothy *et al.*, 1990; Tarmizi and Marziah, 1995).

6.2.3 Physiology and biochemistry of plants in culture

A limited amount of work has been done on the physiology of oil palms in culture, with the aim either of improving establishment after transplanting, or of understanding the flowering problem (Section 6.3). Rival *et al.* (1997) found that clones that were difficult to root exhibited higher peroxidase levels immediately after exposure to NAA for induction of rooting, and suggested using peroxidase inhibitors to improve rooting (see Gaspar *et al.*, 1977). Rival *et al.* (1999) showed that plantlets were photosynthetically active while still in culture.

Morcillo *et al.* (1998) observed that embryoids accumulated the same storage protein (7S globulin) as zygotic embryos, but at less than 2% of the level in the latter. Addition of arginine and glutamine to the medium increased the amount of soluble protein and of 7S globulin per embryoid, but levels remained much lower than in embryos (Morcillo *et al.*, 1999). Bertossi *et al.* (2001) found that abscisic acid improved embryoid tolerance to rapid desiccation, and induced a delay in shoot development during subsequent culture on hormone-free media. No information on the effects of these treatments on regenerated plantlets has yet been published. Jones (1990) found that the endogenous cytokinins in embryoids and zygotic embryos differed, with generally much higher levels in the latter, and with different cytokinins predominating.

6.3 ABNORMAL FLOWERING, BUNCH FAILURE AND OTHER PROBLEMS

Somaclonal variation (genetic variation induced by tissue culture) is a considerable problem with many crops, but data from the first oil palm clone trials indicated a high degree of uniformity and no evidence for somaclonal variation. Embryoid cultures appeared cytologically normal (Jones *et al.*, 1982) and the phenotypic variation between palms within a clone for fruit and bunch characters was no greater than the variation between measurements on the same palm, confirming the expected genetic uniformity (Wooi *et al.*, 1982; Corley *et al.*, 1982). However, this initial optimism was

shattered in 1986, just as commercial-scale planting of clones was about to start, by the discovery of abnormal flowering in some clones.

6.3.1 Mantled fruit

In 1986, it was noticed that some clones planted in 1982 were not flowering normally, but instead had a high incidence of flowers with the mantled character (rudimentary stamen primordia in female flowers developed into supplementary carpels; see Section 2.2.2.6; Plate VIII, D). This abnormality was accompanied by parthenocarpic (seedless) fruit set and severe bunch failure (Corley *et al.*, 1986), and several hundred hectares of clonal palms subsequently had to be uprooted and destroyed because of the problem. Over the next few years, almost all laboratories working on oil palm tissue culture observed the same abnormality.

6.3.1.1 Frequency and severity of abnormal flowering

The frequency of abnormal flowering varies greatly between clones, with some clearly being more susceptible than others (Durand-Gasselin *et al.*, 1995). Typically, an average of 5–10% of palms may be affected (e.g. Wong *et al.*, 1999a; Rival, 2000). In some clones, but not all, male inflorescences are also affected, with the stamens developing into carpel-like structures. The severity of the condition varies between clones, between palms within a clone, and even between bunches on the same palm. The worst affected palms have 100% mantled and parthenocarpic fruit in every bunch, and suffer complete bunch failure. In less severe cases, only a proportion of fruit is mantled, and bunch failure may not occur. Individual flowers may also be only partly mantled, with not all of the stamen primordia developed into supplementary carpels. Partially abnormal palms may not suffer from parthenocarpy, and bunches with some mantled fruit may ripen normally (Ho and Tan, 1990). In such palms, the oil content of bunches may be much the same as from normal bunches of the same clone (Ho and Tan, 1990; Corley, 1993; Maheeran *et al.*, 1995), and oil yield is not affected.

A variety of different treatments was tested with the aim of ‘curing’ abnormal palms, but without success (Donough, 1990). However, spontaneous reversion may eventually occur (Paranjothy *et al.*, 1995a; Duval *et al.*, 1997). Partially affected palms may recover more or less completely within 5 years after planting; in more severely affected palms recovery has also been observed, but takes longer, with only 50% recovered 9 years after planting (Duval *et al.*, 1997).

6.3.1.2 Causes of abnormal flowering

Corley *et al.* (1986) observed that the frequency of mantled flowering increased, in successive years’ plantings of the same three clones, from zero in the first year to 25% in the second, and to 90% in the third year. This suggested that time in culture might be a causal factor, and Paranjothy *et al.* (1995a) showed that the proportion of abnormal plants regenerated increased with the number of subcultures a clone had undergone. However, Durand-Gasselin *et al.* (1999c) found no relationship between time in culture and degree of abnormality, with some clones still giving normal plants after 11 years in culture.

It has been shown that the frequency of abnormality is higher in clones derived from fast-growing callus than from slow-growing, nodular callus (Duval *et al.*, 1988; Besse *et al.*, 1992). Much subsequent work was devoted to searching for differences between these callus types, but Jones *et al.* (1995) noted that abnormal palms had also sometimes been obtained from nodular callus. Eeuwens *et al.* (2002) described the results of a 15-year programme of trials on the effects of culture media on the incidence of abnormality, and it is clear from their work that the medium on which embryoids are cultured has a large effect. Table 6.1 shows that the incidence of abnormality was higher with shorter intervals between transfer to fresh medium, and that low auxin and high cytokinin levels in the medium increased incidence. From these results, it appears probable that it is time under predisposing culture conditions which is the important factor in development of the abnormality, rather than total time in culture *per se*. Under appropriate culture conditions, therefore, there may be no need to limit the time for which an embryoid line is maintained in culture (Section 6.2.1.2).

In molecular or biochemical terms, the cause of abnormal flowering is not known. It has been widely assumed to be an ‘epigenetic’ phenomenon: a modification of gene expression, passing from one cell generation to the next, but reversible by appropriate stimuli, and not involving a change in the DNA sequence. The mantled flowers are very similar to the *poissoni* fruit type (see Section 2.2.2.6), which is believed to be controlled by a single gene. However, the abnormality in palms from tissue culture does not behave like a simple Mendelian mutation. It varies in degree, rather than having an ‘all or nothing’ effect, it is reversible (see above) and it is not simply or consistently inherited. Rao and Donough (1990) and Paranjothy *et al.* (1995a) showed that offspring of partially mantled palms may themselves be partially mantled, although at a much lower level than their parents.

Table 6.1 Effects of culture conditions on incidence of mantled flowering

Treatment	Palms recorded	% mantled	Significance of χ^2 -test
Transfer interval			
4 weeks	321	22	$p < 0.001$
8 weeks	250	7	
NAA level			
0	266	22	$p < 0.001$
0.1 mg/l	195	15	
0.5 mg/l	110	2	
Kinetin (K) level			
0	206	6	$p < 0.001$
0.05 mg/l	209	17	
0.25 mg/l	156	26	
Best: 8 weeks, 0.5 mg/l NAA, 0–0.25 mg/l K	33	0	
Worst: 4 weeks, 0 NAA, 0.05 mg/l K	63	46	

From Eeuwens *et al.* (2002)

Pooled data for four clones. Embryoids were freshly initiated from callus and cultured for 48 weeks as shown. Plants were then regenerated, transferred to the field and monitored for production of mantled flowers. Numbers per treatment varied, depending on survival through transplanting.

Jones (1995), in a review of the flowering problem, drew the following conclusions.

- The transmission through meiosis is imperfect, with maternal associations suggesting cytoplasmic inheritance (Rao and Donough, 1990).
- Although no changes in nuclear or mitochondrial DNA have been detected so far, only a limited number of probes has been used (Cheah and Wooi, 1995; Chowdhury, 1995; Rival *et al.*, 1998a, b).
- The phenomenon is reminiscent of the operation of some of the homeotic genes controlling flower development in other species. This suggestion was made by Ho *et al.* (1991), but Agamuthu *et al.* (1996) failed to detect differences between normal and abnormal palms using a molecular probe based on the *Antirrhinum* Deficiens gene.
- There is clear evidence that the abnormality is accentuated by the addition of cytokinin to the culture medium (Section 6.3.1.1). There is also evidence of disturbed cytokinin metabolism, but little agreement between laboratories. There are reports of increased cytokinin levels in abnormal compared with normal tissues (Paranjothy *et al.*, 1990; Agamuthu and Ho, 1992), but other work (Besse *et al.*, 1992; Jones *et al.*, 1995) indicates that tissues from abnormal palms contain less cytokinin than normal palms.

When normal and abnormal embryoid lines within the same clone (classified according to the flower type

of terminal inflorescences, see below) were compared, there were significant differences, with normal cultures having higher levels of several cytokinins (Jones *et al.*, 1995). Differences between clones were much greater than between normal and abnormal lines within a clone, however. The role of cytokinins is still unclear. As Jones (1998) noted, there has been a tacit, but totally unwarranted, assumption that if cytokinin in the medium was the causal agent of the flowering problem, this would be reflected in disturbed cytokinin metabolism years after the regenerant plants had been removed from the culture medium.

The only significant new work published since Jones' 1995 review is the demonstration that normal and abnormal plants differ in the degree of methylation of nuclear DNA (Jaligot *et al.*, 2000; Rival *et al.*, 2000; Matthes *et al.*, 2001). This is not surprising, as DNA methylation is known to be involved in regulation of gene expression. It is also known to vary as a result of tissue culture in other species, and has been suggested as an underlying cause of somaclonal variation (see Kaeppler *et al.*, 2000, for a review of somaclonal variation in plants).

Eeuwens *et al.* (2002) speculated that kinetin might reduce the level of DNA methylation, as has been shown for other species. The effect of transfer interval may be related to the rapid breakdown of kinetin in the medium; Jones and Hanke (1992) showed that kinetin in the medium had a half-life of less than 2 weeks, so frequent transfer to fresh medium would help to maintain a high

kinetin level. NAA may accelerate the degradation of kinetin, or counteract its effect on the tissues. However, these hypotheses do not explain the fact that a short transfer interval increased the level of abnormality even on a medium with no growth regulators.

6.3.1.3 Conclusions

We still have no clear idea as to what causes the abnormal flowering problem at the molecular or biochemical level, but we have good evidence that low auxin and high cytokinin in the medium, and short transfer intervals, will increase the risk. By avoiding these treatments, the level of abnormality should be kept very low in most clones. A level of up to perhaps 5% abnormality is probably commercially acceptable, given that affected palms may recover, and that seedling fields also contain a small proportion of very low yielders.

6.3.2 Other abnormalities

There are two other commonly observed abnormalities: self-pruning or truncated leaf syndrome (TLS), and terminal flowering. TLS is commonly observed within the first few weeks after transplanting from culture; leaves show a necrotic line, usually leading to complete breakage, transversely across the lamina (Plate VIII E). The symptoms resemble the results of grasshopper damage. All except the most severely affected palms eventually recover. Tan C.C. *et al.* (1999) suggested that the disorder might be caused by boron deficiency. Tan Y.P. *et al.* (1996) demonstrated that the abnormality also occurs in seedlings derived from clonal parents, indicating possible inheritance.

Terminal inflorescences, with the apical meristem becoming floral and vegetative growth ceasing, have been seen as a very rare abnormality in seedling nurseries, but with clonal material they are common, although they are more often found in culture than in the nursery. Their frequency increases with time in culture, and is greater on media with cytokinin than without (Paranjothy *et al.*, 1990). Many terminal 'inflorescences' have structures that are unrecognisable as oil palm inflorescences (illustrated in Tarmizi *et al.*, 1999), but others closely resemble single spikelets from normal inflorescences (Plate VIII F). Careful dissection of these spikelets shows that the flowers can have either normal or mantled structure, so the suggestion (Paranjothy *et al.*, 1990) that the development of terminal inflorescences is associated with the mantled fruiting problem appears incorrect.

In addition to the above, stunted growth and other vegetative abnormalities are sometimes observed. In general, such plants can be detected and removed at the nursery stage.

6.3.3 Testing for abnormalities

Abnormal flowering appears to be influenced by the culture conditions, but is not seen until 2 or 3 years after the clonal palms are planted out in the field. The possibility of detecting the abnormality before the palms reach the field has, therefore, attracted much attention. The ideal would be a simple method of screening at the culture stage to identify lines that will give abnormal palms. A variety of methods has been tried, concentrating on molecular markers, but with little success so far. In some studies, differences between normal and mantled palms have been found (in proteins – Marmey *et al.*, 1991; in cytokinins – Besse *et al.*, 1992; Jones *et al.*, 1995; in DNA markers – Cheah *et al.*, 1993; Paranjothy *et al.*, 1995b; Sharifah *et al.*, 1999; in messenger RNA – Rajinder and Cheah, 1996; Toruan-Mathius *et al.*, 1998; Rival *et al.*, 1998b, 2001; Rajinder *et al.*, 2001; Tregear *et al.*, 2002), but none of these have been confirmed as sufficiently repeatable to be useful as a screening method. Jaligot *et al.* (2000) found differences in the degree of DNA methylation, and Jaligot *et al.* (2002), using methylation-sensitive restriction enzymes, were able to show consistent differences in RFLPs between normal and abnormal material across several different clones. This is the most promising result so far, and needs to be more extensively tested.

Corley (1993) showed an association between the structure of flowers in terminal inflorescences and the later behaviour of other palms of the same clone in the field, and suggested that terminal flowers could be used as a method of screening for the mantled character. Eeuwens *et al.* (2002) used this method to classify the 'mantling risk' of clones, before using them in experiments on the flowering problem. However, many clones do not produce such terminal inflorescences.

Until a marker for the abnormality has been found, the best approach may be to screen clones for sensitivity during the clone testing phase. If a proportion of cultures is maintained under conditions known to induce mantling (high kinetin, low NAA, short transfer interval), additional plants from these cultures could be interplanted in the clone trial and removed as soon as their flowering behaviour has been observed. This would allow the more sensitive clones to be identified and excluded before commercial-scale propagation started.

6.4 CLONE TESTING

Ultimately, the success of clonal propagation will depend on the identification of clones with sufficiently high yields to justify the additional cost of tissue culture,

compared with production of seed, and perhaps of screening to eliminate abnormalities. An early estimate of the costs of propagation by tissue culture gave a cost per plant over five times that of a seedling (Corley *et al.*, 1988), and Rival (2000) also estimated the cost of a ramet at five times the cost of a seed. Putting this figure into a financial model indicated that a yield increase of 20% would be needed if clonal planting were to be profitable (Corley *et al.*, 1988). Profitability depends heavily on the palm oil price and also on the financial discount rate, but this gives an indication of what the target should be in clone development.

6.4.1 Ortet selection

The first step in identification of high-yielding clones is to select genetically superior ortets. Ortet selection presents problems particularly for bunch yield, since variation in individual palm yield has a low genetic component. The greater the proportion of total variation that is due to genetic factors (the broad sense heritability, see Section 5.2.6.2), the more successful selection is likely to be. Yield of fresh fruit bunches (FFB) is often more affected by microenvironment and interpalm competition than by genetic factors, whereas variation in oil/bunch has a large genetic component, so selection for the latter is likely to be more successful. There are various ways in which the efficiency of selection might be increased. Soh (1986) showed that selection of the best families, followed by selection of the best individual palms within those families, would give greater progress than selection of individuals without regard to family. Soh and Chow (1989) found that selection for a combination of yield components would be more efficient than direct selection for oil yield alone. Breure and Corley (1983) showed that selection for high bunch index would be a good way of identifying palms suited to high-density planting. Baudouin *et al.* (1987, 1995) and Baudouin (1987) used a smoothing technique to allow for environmental variation within a field, and indicated that this increased the efficiency of selection.

Hardon *et al.* (1987) estimated that it should be possible to identify clones yielding at least 30% more oil than the seedling population from which the ortets were selected. Soh (1986) questioned this; using data from Malaysian progeny trials he found a low broad sense heritability for oil yield, and estimated that simply choosing the highest yielding individuals within a high-yielding progeny would be likely to give only a 16% increase, while the risk of missing the highest yielders would be appreciable. Baudouin and Durand-Gasselin (1991; see Section 5.3.2) found much higher broad

sense heritabilities for oil yield than Soh (1986), and Meunier *et al.* (1990) considered that after a second stage of clonal selection a 30% yield increase would be achievable. However, Nelson *et al.* (2000) agreed with Soh that selection of individual palms was unlikely to be very successful, and they planned to develop clones from random seedlings in reproductions of the best families identified in progeny trials. Nelson and Caligari (2002) suggested that choice of family should be based on the mean and variance, rather than just the mean. With the same mean, a family with large variance is more likely to include outstanding individuals than one with small variance. This approach can be applied simultaneously to more than one characteristic, such as yield and height.

6.4.2 Clone yields

Clone trial results are now superseding these academic arguments. Corley and Law (1997) listed results of clone trials, and found many examples of clones yielding at least 25% more than seedling standards (see Table 6.2). However, with the exception of the trials described by Donough and Lee (1995), Maheeran and Zarin Othman (1999) and Soh *et al.* (2001), none included as much as 5 years' data, which is probably the minimum needed for reliable clone evaluation (Corley *et al.*, 1988).

From 59 clones, tested in 15 trials in North Sumatra and the Ivory Coast, Cochard *et al.* (1999) identified 12 which outyielded the standard cross (L2T × D10D) by more than 20%, with an average improvement of 27% in oil yield, and three clones yielding more than 30% above the standard cross. It must be noted that the CIRAD-CP standard cross has been in use for many years, and the average yield of 'second cycle' selections is 16% above the standard (Gascon *et al.*, 1988). Thus, the best clones, most of which were selected from 'first cycle' families, are only about 14% better than currently available seedling progenies. The target is constantly moving: by the time a good family has been identified and the best individuals within it have been cloned and tested, a new generation of improved seedling material will be available. Assuming 10% yield improvement per generation of breeding (see Section 5.5.2), clones that are 30% better than the generation from which they were selected may only outyield the best seedlings by 20%.

The choice of seedling standards in clone trials may present problems. Comparison with a repeat of the cross or crosses from which the ortets were selected gives information on selection progress, but may not be of practical relevance if the crosses were not similar to those that might be planted commercially. Comparison has sometimes been made with unspecified commercial

Table 6.2 Yields of oil palm clones, compared with seedling standards

Location	Trial no.	Years recorded	Seedling standard ^a	No. of clones	Oil yield (t/ha)		Yield as % std		Ref.
					All	Best	All	Best	
Ivory Coast	GP-54/63	3	L2T × D10D	4	4.66	4.90	128	134	1
Ivory Coast	GP-64	4	D8D × L9T	5	3.9	4.3	131	143	2
Ivory Coast	GP-65	2	D115D × L2T	7	2.66	2.95	81	90	1
Ivory Coast	GP-70	4	L2T × D8D	5	3.6	4.1	103	117	2
Ivory Coast	GP-71	4	L10T × D8D	8	4.6	5.2	100	113	2
Ivory Coast	GP-76	2	L2T × D10D	5	3.4	3.8	117	131	2
Sumatra	BB-CL2	4	L2T × D10D	4	7.35	8.9	102	124	2
Sumatra	BB-CL3	3	L2T × D10D	9	7.66	9.8	113	144	2
Sumatra	BB-CL4	3	C2501	9	4.99	6.5	87	113	2
Sumatra	BB-CL5	3	C2501	9	5.61	6.1	109	118	2
Sumatra	AK-GP23	3	L2T × L404D	4	6.18	8.3	88	119	2
Sumatra	AK-GP24	3	BB703D × BB50	19	5.92	6.9	106	123	2
Malaysia	10	2	Deli × La Mé	3	3.48	4.00	99	113	1
Sumatra	BJ26S	3	ns	14	6.6	7.5	114	129	3
Malaysia	C3	8	ns	7	6.6	7.5	125	142	4
Malaysia	C7	5	ns	8	8.6	9.5	125	138	4
Malaysia	C12	5	ns	10	8.1	9.0	129	143	4
Malaysia	C13	5	ns	8	8.1	9.4	129	149	4
Malaysia	BCT3-87	3.5	Deli × Avros	7	2.48	3.08	77	96	5
Malaysia	PB145	3.5	GRC D × P	7	2.08	2.57	80	99	5
Malaysia	BCT2-86	3.5	Deli × Avros	4	3.52	3.81	100	109	5
Malaysia	UP17.56	2	Deli × Ybi	20	7.08	9.54	85	114	5
Malaysia	PB150	2	GRC D × P	6	3.02	4.18	93	129	5
Malaysia	BCT4-89	9	GH D × P	12	6.9	8.6	95	118	7
Malaysia, coastal	mean of 5	7	GH D × P	8	6.28	7.17	91	104	6
Malaysia, inland	HCT 6	7	GH D × P	8	4.90	5.67	86	100	6
Malaysia, inland	PCT 11	10	GRC D × P	5	4.21	4.92	109	127	6

Based on Corley and Law (1997), updated where new data have been published. Where more than one standard was included in a trial, the best was used for comparison.

^ans: not specified; GRC: Guthrie Research Chemera; GH: Golden Hope.

References: 1: Le Guen *et al.* (1991); 2: Duval *et al.* (1997); 3: Hutomo *et al.* (1996); 4: Maheeran and Zarin Othman (1999);

5: Soh *et al.* (1995); 6: Donough and Lee (1995); 7: Soh *et al.* (2001).

dura × *pisifera* (D × P) material, but given the range of yields among D × P material from different suppliers (e.g. Rajanaidu *et al.*, 1986b), such comparisons may not be very informative. Corley *et al.* (1988) suggested that known individual progenies would be the best standards, but even where individual crosses are used, results can be confusing. In the trials of Le Guen *et al.* (1991), for example, cross D8D × L9T yielded 13% more than D115D × L2T in trial GP-54/63, but 30% less in trial GP-65. There are several possible reasons for such discrepancies: numbers per cross may be small, and a combination of small sample size, genetic variation between individuals, and genotype × environment (G × E) interactions can result in very different performance of the same cross in different trials (some of these points are also true for clones; see below).

The best approach appears to be to use a set of several standard crosses, each recorded individually to give the maximum amount of information, and to allow any anomalies to be identified. An organisation such as the Malaysian Palm Oil Board (MPOB) could provide a very useful service by supplying such a set of standards to the industry.

An important exercise in clone trials is to check that all palms are of the intended clone. It is easy for mistakes to be made in the laboratory or the nursery, and if misidentified palms occur in trials, results will not be as expected. Many clones are easily distinguished by morphological characteristics (petiole colour, spine length, fruit morphology). Molecular markers may also be used (see Section 5.2.8), but a visual inspection is cheaper.

Table 6.3 Performance of clones in different environments

Clone	FFB (% site mean)		Oil/bunch (%)		Oil Yield (% site mean)	
	Coastal	Inland	Coastal	Inland	Coastal	Inland
34A	86	88	24.4	22.4	84	86
54A	113	116	23.1	21.9	105	111
90A	112	96	24.5	22.8	110	95
115E	86	89	29.2	28.0	101	108

Yields recorded for 7–11 years, in five coastal trials and six inland trials.

From Donough and Lee (1995) (trials included other clones in addition to those shown).

6.4.3 Clone adaptability

6.4.3.1 Clone × environment interactions

Where the same clones have been tested on different sites, significant clone × environment interactions have been observed (Lee and Donough, 1993; Corley *et al.*, 1995b). Table 6.3 shows an example: oil/bunch was consistent between coastal and inland sites, with clone 115E being exceptional in both environments, but FFB yield of clone 90A was good on coastal sites, but poor inland. G × E interactions are discussed further in Section 5.5.1.7. The implication of such interactions is that performance at one site will not be a good guide to performance elsewhere. It should be possible to identify clones specifically adapted to particular environments. Conversely, though, planting a clone under conditions in which it has not been tested will be to risk disappointment. Soh *et al.* (2001) suggested that a minimum set of trial sites representative of environments where clones are to be grown needs to be identified.

Clones differ in susceptibility to *Fusarium* wilt (Corley, 1993; de Franqueville *et al.*, 1995) and to *Cercospora elaeidis* (Corley *et al.*, 1988), and perhaps to *Ganoderma* (Durand-Gasselin *et al.*, 1999c). Differences between clones in physiological responses to drought have been described by Lamade *et al.* (1998b).

6.4.3.2 Flowering patterns

Within a single trial, individual clones show a high degree of uniformity in seasonal flowering patterns (Corley, 1980), with all palms tending to be in the same phase of the sex cycle at any given time. This could lead to shortage of male flowers and poor fruit set at certain times in monoclonal plantings, and Corley *et al.* (1982) suggested planting mixtures of clones to avoid such problems. However, uniform flowering should lead to uniform fruiting, so that all palms tend to carry ripe bunches simultaneously. That could give increased

harvester productivity, and might eventually permit mechanisation of harvesting.

6.4.3.3 Management of clones

Clones have been shown to differ in their fertiliser requirements (Donough *et al.*, 1996b), and the possibility of taking advantage of uniform fruiting to improve harvester productivity has already been mentioned. Significant differences between clones in optimal planting density have been observed (Corley and Donough, 1992; Smith *et al.*, 1996). These observations point towards monoclonal plantings, but mixtures of clones may be needed to ensure good fruit set (see above) and could also reduce the risk of catastrophic disease loss. A compromise would be to plant a mixture of clones, grouping together clones of similar vegetative stature to allow for differences in optimal planting density, in strips of four rows per clone. Each strip could be managed individually, while pollen spread between strips would overcome potential fruit-set problems.

6.5 THE FUTURE FOR OIL PALM CLONAL PROPAGATION

6.5.1 New tissue culture methods

Clonal propagation by culture on solid media is now routine in many laboratories. However, results with any given clone remain unpredictable, with embryoid proliferation being the main bottleneck, as noted in Section 6.2.1.2. As Rival (2000) said, ‘customer requirements have to fit in with the vagaries of production, which is not satisfactory from a commercial point of view’. This has stimulated interest in alternative methods, but at the same time the realisation that the amount of somaclonal variation may depend on the culture media or conditions (Section 6.3.1.1) has greatly extended the

necessary time scale for development of new methods. It is not sufficient to monitor culture growth rates or frequency of embryogenesis; any new method must also be tested through to the stage of flowering in the field, to ascertain that the palms produced are normal.

6.5.1.1 Suspension culture

Culture of a suspension of cells in a liquid medium offers the possibility of automation of the tissue-culture process, eliminating the hand labour required for transfers on solid media, and with synchronised development allowing the possibility of timing production to meet customer needs. The first work on suspension cultures was by Hughes *et al.* (1983), and successful regeneration of plants was reported soon afterwards (Malaurie, 1987; de Touchet *et al.*, 1990; Teixeira *et al.*, 1990). A full description of the method was given by Teixeira *et al.* (1995), who observed much faster growth rates than on solid medium. Duval *et al.* (1995b) quoted a cost of US\$0.20 for an embryoid from suspension culture, to which was to be added the cost of 'germination', rooting and hardening. However, it is only the embryoid proliferation stage that is replaced (suspension cultures are developed from callus or embryoid cultures established on solid medium in the standard way), and according to Wong *et al.* (1999a) costs were only 30% lower than for propagation on solid media. Bulk handling of shoots at the rooting stage may reduce costs further (Zamzuri, 1999).

Tahardi (1998) described results with periodic immersion of callus in liquid, rather than continuous liquid suspension culture, based on a method described by Teisson *et al.* (1995). The method gave rapid growth and synchronised embryoid development, without the 'vitrification' said to be a problem with suspension culture (formation of translucent structures, with a watery appearance, which fail to develop further).

Field trials of clones propagated by suspension culture are in progress (Soh *et al.*, 2001). Preliminary data indicate that the risk of abnormal flowering is no greater than with culture on solid media: of 2600 plants flowering, less than 4% were abnormal. This result is very promising: if costs could be reduced by the use of suspension culture, then the yield increase needed to make clones profitable would be smaller.

6.5.1.2 Artificial seeds

There has been some discussion of the production of artificial seeds, but little work published with oil palm. The concept is to produce synchronised batches of

embryoids from suspension culture and, after suitable treatment, to encase them in beads of an alginate gel. A degree of desiccation would probably be necessary (see Section 6.2.3), this would render the embryoids 'dormant', so that growth would only recommence after the moisture content was raised. The advantage of such a procedure would be to allow large numbers of plantlets to be developed simultaneously, to fit in with seasonal requirements for planting programmes. However, it is not clear how the endosperm food reserve would be replaced.

6.5.2 Recycling through culture

Clone testing takes 7 or 8 years. During that time, the clones must be maintained in some way, so that after testing the best can be propagated commercially. The possibility of cryopreservation has already been mentioned (Section 6.2.2.1), but a simpler approach is to reclone the best from ramets in the field. Paranjothy *et al.* (1990) suggested that such recycling might 'deregulate the mechanism causing the abnormality'; in other words, reset the material back to normal. Conversely, it has been suggested that recycling might increase the risk of abnormality (Soh, 1998), but neither view appears to be correct. Wong *et al.* (1999a) found a small increase in abnormality, with 7% among 68,000 plants from primary cultures and 11% among 39,000 plants from recloning. However, their figures indicate that an average of 1630 plants per clone were produced after recycling, but only 860 from primary cultures. Thus, the increase in percentage abnormality could be attributable to a longer period in culture, rather than to recycling. Later results from the same laboratory were encouraging, with less than 5% abnormal palms after recycling, either on solid media or in suspension culture (Soh *et al.*, 2001). If recycling can be done safely, it will not be necessary to maintain the same lines in culture for very long periods. Regular resampling from the field would allow a maximum time in culture to be set, without limiting the total numbers per clone produced.

6.5.3 Commercial developments

Commercial planting of clones has started, on a limited scale. Table 6.4 summarises the information that we have been able to collect. These data are not comprehensive; there are undoubtedly other plantings which we are not aware of, but the table shows that, at the end of 2000, there was a total of over 10,000 ha of clones planted world-wide. This area is steadily increasing, as more organisations extend their plantings, but compared

Table 6.4 Areas of clonal palms planted, in trials and commercial plantings, 2000

Location	No. of clones	Area planted (ha)			Ref.
		Trials	Comm.	Unspec.	
Malaysia	130	175	2,700	–	1
Malaysia	–	–	–	150	2
Malaysia	156	82	380	–	3
Malaysia	80	–	–	1,553	4
Sabah	50	–	294	–	5
Sarawak	–	–	450	–	5
Ivory Coast	216	–	–	800	6
Papua New Guinea	–	15	–	–	7
Costa Rica	131	97	–	–	8
Indonesia	71	140	–	–	9
Indonesia	165	–	–	2,200	10
Indonesia	–	84	–	–	11
Total		593	3,824	4,703	

Where areas were not specified, data were calculated assuming 143 palms/ha.

References: 1: G. Wong (pers. comm., 2000); 2: Khaw and Ng (1997); 3: Gurmit Singh (pers. comm., 2000); 4: A. Maharan (pers. comm., 2001); 5: Simon *et al.* (1998); 6: Rival (2000); 7: S. Lord (pers. comm., 2000); 8: R. Escobar (pers. comm., 2000); 9: S. Nelson (pers. comm., 2000); 10: IOPRI (unpubl.); 11: Socfindo (unpubl.).

with a total of over 6 million hectares (see Chapter 1), it is insignificant as yet. In some instances, the same clones have been planted in different places, but there were probably more than 700 clones under test. Few commercial yield figures from clones have been published. Simon *et al.* (2001) compared a 3 ha plot of clones with seedlings, and obtained a 35% greater oil yield from the clones over the first 7 years of production. Larger blocks gave comparable results, but over shorter periods.

As noted above, early estimates of the costs of propagation by tissue culture gave a cost per plant over five times the cost of a seedling, and a financial model indicated that a yield increase of 20% would be needed for clonal planting to be profitable (Corley *et al.*, 1988). More recently, Zamzuri *et al.* (1998) indicated that investment in a tissue-culture production laboratory would only be profitable at a selling price of RM15–20 per plant, more than ten times the price of a germinated seed. If the costs of clone testing are also included, there appears to be a gap between the price required for profitable production and that acceptable to the grower. This gap could be closed if the use of suspension culture reduces production costs (Section 6.5.1.1) and if clones giving yield increases of more than 30% can be identified (Section 6.4.2).

Clonal seed is an alternative to clones (see Section 5.4.5.2). This requires the clonal propagation of proven *dura* and *pisifera* seed parents, to allow production of large quantities of seed of the best individual crosses. Soh (1986) estimated that the best families might yield 13% above the population mean, while Breure and Bos (1992) considered that as much as 30% might be possible. Much depends on the variability in the starting population, but in either case, the yield advantage would only be that of the best families, rather than the best individuals within those families. Costs would not be much greater than for conventional seed, though, and extensive clone testing would not be required, as the best crosses would already have been identified in progeny trials. Corley and Law (1997) estimated that in some circumstances clonal seed could be developed in at least 4 years less than *tenera* clones. Jacquemard and Durand-Gasselin (1999) agreed with this estimate, but considered that the balance of risks, costs and potential genetic progress favoured cloning of elite individual ortets.

6.6 OTHER ASPECTS OF OIL PALM BIOTECHNOLOGY

Apart from tissue culture propagation, there are several other applications of biotechnology to the oil palm; some are discussed below, while the use of molecular markers, an important area of biotechnological research, is described in Chapter 5.

6.6.1 Other tissue culture techniques

6.6.1.1 Microspore culture

The aim of clonal propagation is to produce genetically homogeneous clones. An alternative way of producing homogeneous planting material is by crossing homozygous lines (with two sets of identical chromosomes) to produce F1 hybrids. Microspore culture offers a method of producing homozygous lines without the eight or more generations of repeated selfing required for conventional inbred lines: cultures are developed from haploid pollen mother cells (with a single set of chromosomes), and the chromosome number is doubled by treatment with the cell division inhibitor colchicine, to give cells that are homozygous and diploid. Some preliminary work on culture of oil palm microspores has been published (Odewale, 1989; Latif, 1991; Tirtoboma, 1998), but as yet there are no reports of homozygous diploid plants being produced.

Jones (1989) discussed the problems of testing the homozygous *duras* and *teneras* that might be developed from anther cultures. Such palms could not be judged on phenotypic performance, but progeny testing even relatively small numbers would involve several hundred hectares of trials. Barley breeders may produce as many as 100,000 doubled haploids every year; progeny testing such numbers of oil palms would require thousands of hectares of trials. This is probably the main reason that this approach has not received greater emphasis from oil palm breeders. Using molecular markers to identify the most promising combinations before planting might help to reduce the scale of testing required.

6.6.1.2 Protoplast culture

There has been some interest in protoplasts, plant cells with the cellulose walls removed. Protoplast fusion has been proposed as a method of creating 'hybrids' between sexually incompatible species, but there is no obvious application for this in oil palm. Protoplasts have also been considered as possible material for genetic engineering; it should be easier to insert foreign DNA into a cell without a cell wall. In practice, though, protoplasts have been little used for transformation in other species, *Agrobacterium* and particle bombardment being the preferred methods of DNA insertion (Section 6.6.2.3). Although there has been some work done with oil palm protoplasts (Wong, 1977; Vouyouklis, 1981; Bass and Hughes, 1984; Sambanthamurthi *et al.*, 1996, 2000a; Budiani *et al.*, 1998) this does not appear to be a productive line of research.

6.6.2 Transformation

Genetic engineering (DNA transformation) is likely to become important in future, offering as it does a means

to achieve objectives that would be difficult or impossible by conventional breeding. There are four essential components to transformation: the identification and cloning of the target gene or genes, the identification of promoters or regulatory genes, to control when and where the target gene is expressed, and the actual insertion of these genes into cells of the plant, followed by regeneration of transformed whole plants. With oil palm, significant progress has been made in all these areas. Target genes will often be genes coding for new enzymes not already present, to give the plant a function that it did not have, but two other sorts of change are also possible. Gene activity can be increased by inserting additional copies of the genes, or activity can be eliminated by the antisense method. This involves the insertion of a synthetic gene with a DNA sequence that complements the target gene, and so cancels out its activity. In every case, the target genes must be combined with suitable promoters to regulate when and in which tissues they are active.

6.6.2.1 Targets for transformation

Possible objectives for transformation of oil palm include both agronomic characteristics, such as disease or pest resistance, and quality traits, particularly oil composition (all of which are also targets for conventional breeding, see Chapter 5). Among agronomic characters, modification of the enzymes involved in fruit abscission, which are now well understood (Henderson *et al.*, 2001), could be useful in relation to harvesting.

Parveez *et al.* (1994) reviewed the current status of genetic engineering in other oil crops, and listed ways in which oil composition might be changed. An increased proportion of oleic acid has been identified by MPOB as a way of increasing the market share for palm oil (Soh *et al.*, 1994b). The pathway for oil synthesis is set out in Fig. 6.1. Soh *et al.* (1994b) suggested that oleic

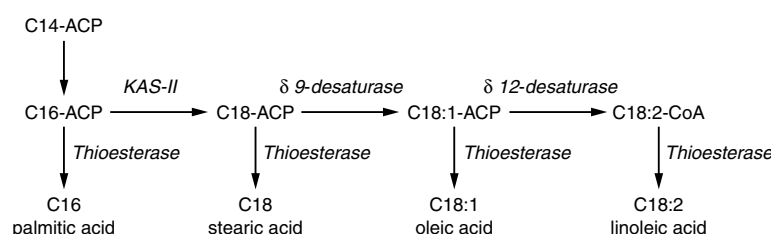


Fig. 6.1 Oil synthesis pathway in plants. Enzymes catalysing each step in the biosynthetic pathway are shown (names in italics). C14, etc., indicates number of carbon atoms in the fatty acid; KAS-II: 3-keto-acyl-ACP synthetase II; ACP: acyl carrier protein; CoA: coenzyme A; $\delta 9$ and $\delta 12$ indicate the positions in the fatty acid carbon chain at which the desaturases operate.

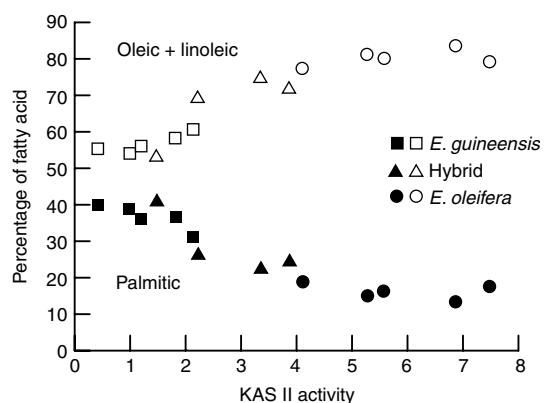


Fig. 6.2 Fatty acid composition of oils from palms with different levels of KAS-II activity, showing increasing unsaturated acids with increasing activity. (Data from Sambanthamurthi *et al.*, 2000a.)

content might be increased by increasing the activity of KAS-II, or using antisense to reduce the activity of C16-ACP thioesterase, or both. High palmitic soya bean mutants have been shown to have low KASII activity (Wilson *et al.*, 2001), and Sambanthamurthi *et al.* (2000a) found correlations between KAS-II activity and iodine value, palmitic acid and oleic acid contents in a range of *Elaeis guineensis* and *E. oleifera* genotypes (Fig. 6.2). However, Fig. 6.1 also illustrates some of the uncertainties: the suggested changes would undoubtedly increase the proportion of C18 fatty acids relative to C16, but it is not clear that increased oleic acid would be the main result. Levels of stearic and linoleic acids might also change, and which changed most would depend on relative activities of the desaturases and the thioesterases, some of which may show a preference for a particular fatty acid. Siti Nor Akmar *et al.* (2001) argued that δ^9 -desaturase is highly active, so that a reduction in KAS-II activity would lead to increased C18:1, not C18. In agreement with this, Sambanthamurthi *et al.* (2000a) found no correlation between KAS-II activity and C18 level.

Other possibilities identified by Parveez *et al.* (1994) included:

- increasing stearic content, by reducing the activity of δ^9 -desaturase
- increasing palmitic acid content, by reducing KAS-II activity
- decreasing saturated fatty acid content by increasing δ^9 -desaturase activity

Some progress has been made in identifying and cloning the important genes. Rashid and Shah (1996)

have determined the DNA base sequence for the oil palm δ^9 -desaturase gene. Shah and Mansor (1997) and Murase *et al.* (1997) isolated and characterised cDNA corresponding to oil palm thioesterases. According to Siti Nor Akmar *et al.* (2001), a cDNA clone of KAS-II has also been isolated.

6.6.2.2 Promoters

Soh *et al.* (1994b) pointed out the need to identify mesocarp-specific regulatory genes, to control expression of the target genes. It will be important to ensure that any changes in oil composition are made only in the mesocarp; lipids are a major component of cell membranes, and changes in membrane composition elsewhere in the plant could be damaging. Siti Nor Akmar *et al.* (1995, 1996, 2001) reported the first steps towards identifying such regulatory genes, with the isolation of mesocarp-specific and kernel-specific complementary DNAs (cDNAs) from oil palm. Kemp and Stratford (2000) identified a β -glucanase gene that was highly expressed in mesocarp tissue with very little detectable expression in other tissues, and also isolated the promoter controlling its activity. Shah and Cha (2000) identified cDNA specific to *E. oleifera* mesocarp, and not found in *E. guineensis*.

6.6.2.3 Transformation methods

Most work has been done with particle bombardment, the 'gene gun', or 'biolistics'. This involves bombarding suitable cells or tissues with minute (1 μ m diameter) tungsten or other metal particles coated in the DNA which is to be inserted. The required DNA is accompanied by a marker gene, usually for antibiotic or herbicide resistance; the cells are then grown on a medium containing the antibiotic or herbicide, and only cells that have acquired the resistance gene survive. The method requires careful adjustment of numerous variables. Useful work has been done on this (Parveez *et al.*, 1996, 1997, 1998a), and Parveez and co-workers have successfully inserted a marker gene into oil palm tissue and regenerated transformed plants (Parveez *et al.*, 1998b, 1999; Parveez, 2000). The next important step will be the insertion of functional genes, rather than simple markers. According to Siti Nor Akmar *et al.* (2001), work is already in progress with δ^9 -desaturase, and with antisense KAS-II, to reduce the activity of the latter enzyme. Haliza *et al.* (2001) described work on an antisense gene to δ^9 -desaturase, for high stearic acid production.

An alternative to particle bombardment is use of the crown gall bacterium, *Agrobacterium tumefaciens*. When

this bacterium infects a plant naturally, it inserts genes into the plant cells that control hormone production, and stimulate gall development. For transformation work, the hormone genes are replaced by the genes it is desired to insert. *Agrobacterium* transformation is the preferred method for dicotyledonous species, but the bacterium does not naturally infect monocots. However, some success with monocots has been achieved, and Chaidamsari *et al.* (1998) have transformed cells in oil palm leaf explants.

6.6.3 Conclusions

It appears probable that transformed oil palms, probably with modified oil composition, will be produced within the next few years. However, it will take many more years before significant volumes of genetically modified palm oil are commercially available. In order to reach that stage, the transformed plants must be tested, to determine which individuals best express the required character, and to eliminate plants in which the transformation has had undesirable side-effects. The selected individuals must then be cloned, and multiplied up to sufficient numbers for commercial planting. All this may take up to 15 years after the point at which transformed plants have been regenerated (Corley and Stratford, 1998).

Despite the long time scale, it is likely that clones of transformed palms will play an increasing part in the oil palm industry of the twenty-first century. It should be remembered, however, that the time scale of development for competing annual oil crops is much shorter. Soya bean, sunflower and rapeseed lines with modified oil composition are already available, developed either by conventional or mutation breeding, or by transformation. The ability of the annual crop grower to switch crops and varieties from year to year means that specialised markets can be more readily supplied by annual oilseeds than by oil palm. Palm oil's relatively low production cost will remain its greatest advantage, and Hardon and Corley (2000) and Tinker (2000a) considered that transformation may play a greater role in further yield increases and cost reductions than in the production of speciality oils. However, production of polyhydroxybutyrate (PHB, a biodegradable plastic) could be of interest. Produced by bacterial fermentation at present, this costs five to ten times as much as polymers such as polyethylene (Houmiel *et al.*, 1999). According to Houmiel *et al.*, three enzymes are needed to synthesise PHB from acetyl coenzyme A, the precursor for fatty acid synthesis, so transforming oil palm to produce PHB should be feasible, and work on this has started (Masani Mat Yunus *et al.*, 2001).

Chapter 7

Seed Germination and Nurseries

7.1 SEED GERMINATION

Oil palm seed is dormant when it is harvested, and under natural conditions germinates sporadically over several years (Rees, 1963d). In a plantation, in order to give uniform seed lots for nursery and field planting in the optimum season, a method of breaking this dormancy is needed. In the early years of plantations the methods used for germinating seed often gave erratic results and germination failures were common. The industry had to await the physiological studies of Hussey (1958, 1959) and Rees (1962c) before a full understanding was obtained of the factors involved. These workers showed that the critical requirement to break dormancy was to maintain the seed at a temperature of 39–40°C for up to 80 days.

7.1.1 The physiology of germination

The anatomy of the oil palm seed is illustrated, and the process of germination described, in Section 2.2.1. In this section, the factors affecting germination, and important in its control, are discussed.

7.1.1.1 Effect of temperature

It was realised early in the history of the plantation industry that a high temperature was needed for the satisfactory germination of oil palm seed (Bucher and Fickendey, 1919). Sand beds, well watered and exposed to the sun, proved acceptable in the Far East until valuable selected seed began to be produced. In West Africa, with its relatively sunless climate, exposure to the sun was not very effective, germination was often poor and, in spite of various systems of applying heat, less than 60% germination was usually obtained.

Hussey (1958) showed that the embryo itself is not dormant, but starts to elongate immediately if it is removed from the kernel. The rate of growth was low, compared with normal germination, but others have shown that excised embryos will grow well on a suitable culture

medium (Bouharmont, 1959; Rabechault, 1962). An embryo still in contact with the kernel would also germinate, provided the operculum was removed or the kernel at the other end of the embryo was cut away, so that the embryo was free to elongate in some direction (Hussey, 1958). Thus, contact with the endosperm did not appear to have an inhibitory effect on embryo elongation.

In contrast to excised embryos, intact kernels without shells remained dormant for up to 6 months (Hussey, 1958). This dormancy could be overcome by heating at 40°C. A high oxygen concentration accelerated germination (Table 7.1) if applied during or after the heat treatment, but not before. While some germination occurred during the heat treatment, a rapid flush of germination occurred on cooling afterwards (Table 7.2), which Hussey attributed to the increased solubility of oxygen at the lower temperature. Hussey (1958)

Table 7.1 Effects of oxygen and temperature on the germination of *tenera* kernels

Germination (%)	Temperature (°C)			
	25	33	40	45
After 4 weeks, in air	0	0	0	0
After 4 weeks, in oxygen	0	0	34	0
After 8 weeks, in air	0	0	5	0
After 8 weeks, in oxygen	0	0	81	0

From Hussey (1958).

Table 7.2 Effect of temperature on subsequent germination of *tenera* kernels

	Temperature (°C)					
	30	34	36	38	40	42
Germination (%)	0	2	11	53	70	0

From Hussey (1958).

Data are percentage germination, in air at 25–27°C, after 2 months of heat treatment.

suggested that a minimum oxygen concentration in the embryo tissues was required for germination, this minimum decreasing with time at a rate dependent on temperature, but why this minimum concentration is required, and why it decreases with time, was not clear. The possibility of an inhibitor of germination which must be destroyed by oxidation is an obvious one; such inhibitors are common in the seeds of other species. However, as already noted, Hussey's experiments with partially dissected embryos indicated no such inhibition, but suggested that the effect of the endosperm might be a mechanical restriction. From heat-treated intact kernels, the embryo elongated rapidly after rupture of the operculum, suggesting a sudden release of pressure. Alang (1982) showed that the heat treatment weakened the abscission layer which borders the operculum, thus reducing the force necessary for the embryo to rupture this layer. Heat treatment also has a direct effect on the embryo: Hussey found that embryos that had not been heat treated elongated only slowly if removed from the endosperm, and Alang showed that the heat treatment increased the osmotic potential of the embryo, so that the force applied to the operculum would be increased.

Hussey (1958) found that long periods at temperatures above 40°C were harmful, but Labro *et al.* (1964) showed that 3 h at 60°C would give 70% germination within 40 days with Deli *dura* seed. However, Menendez (1966) found that only Deli *dura* seed responded to this treatment, and the method does not appear to have been used in practice, presumably because it is less reliable than the conventional dry heat method described below.

The concept of thermal time does not appear to have been applied to oil palm seed germination. Thermal time is expressed in day-degrees, the product of time and temperature, with a base temperature below which the process stops. Many growth processes, including seed germination in some species, show a linear relationship with thermal time. Hussey's results (Table 7.2) indicate that the base temperature is probably about 34°C. At temperatures of 40 and 45°C, the data of Labro *et al.* (1964) show an approximately linear relationship between germination and thermal time above 34°C. At higher temperatures the relationship broke down; although short periods gave good germination longer periods were lethal.

7.1.1.2 Moisture content

Hussey's experiments were done with *tenera* kernels or nuts, because their small size allowed large numbers to be handled easily (Hussey, 1958, 1959). The moisture content of nuts in most of Hussey's experiments was

optimal for germination, which commenced during the heat treatment; this is the wet heat method (Section 7.1.4.2). He showed that germination of *tenera* nuts was poor below 20% or above 26% moisture.

For plantations, *dura* nuts are more important than *tenera*, and Rees' work with these was critical for the development of the dry heat method of germination now in widespread use (Rees, 1961a, 1962c). The optimum moisture content for germination of *dura* nuts is about 22%, but Rees demonstrated that the heat treatment could be applied at a lower moisture content; this would break the dormancy, but did not allow germination. Germination then occurred rapidly as soon as the moisture content of the seed was raised (Fig. 7.1). The dry heat method is now in routine use by all seed producers, and will give over 85% germination of fresh *dura* seeds (Section 7.1.4.1). Rees (1962c) summarised the advantages of the method as including the following.

- The moisture content during heat treatment is not as critical as for the wet heat method; anywhere between 14 and 21% moisture will give satisfactory germination, although for best results a narrower range is preferred (Section 7.1.4.1).
- All germination occurs within a few weeks, thus making prenurseries more uniform.
- 'Brown germ' disease (see Section 12.1.1) is favoured by high temperature; because no seed germinates during heat treatment, the disease is less of a problem than with the wet heat method.

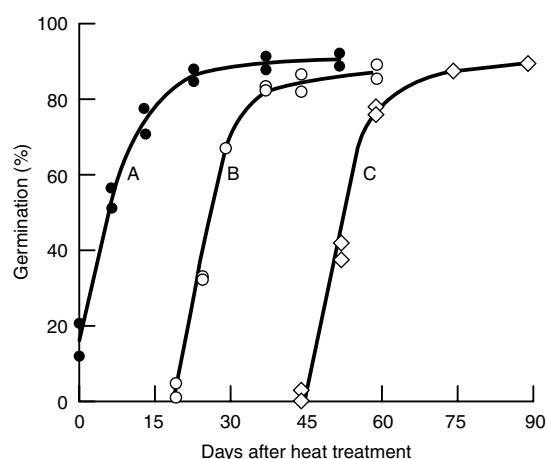


Fig. 7.1 Effect on germination of wet and dry heat treatment, and storage of heat-treated seed. (A) Wet heat: seed heat-treated at optimum moisture content for germination; (B) dry heat; (C) dry heat, stored for 25 days before bringing to optimum moisture content. (From Rees, 1962c.)

7.1.1.3 Growth regulators

Attempts to stimulate germination with plant growth regulators, to avoid the need for heat treatment, have not been very successful. Hussey (1958) was unable to stimulate germination with auxins. Wan and Hor (1983) obtained faster germination by soaking seed in a 500 µg/l solution of gibberellic acid (GA3) before heat treatment, and Z.C. Alang (pers. comm., 1985) obtained 35% germination of unheated seed with GA3. Herrera *et al.* (1998) obtained 45% germination of *tenera* seeds after soaking for 24 h in a 1.5% solution of hydrogen cyanamide (CH₂N₂), and nearly 90% if the CH₂N₂ treatment (0.75%) was preceded by 10 min in concentrated sulfuric acid. The time to reach maximum germination was about 4 weeks less than with the conventional 40-day dry heat method. Ethephon was also effective, if combined with the sulfuric acid scarification treatment. Only one experiment was done with *dura* seeds, and the best treatment (CH₂N₂ and ethephon combined) gave only 60% germination, but this was without the sulfuric acid pretreatment. These results are encouraging, suggesting that it may be possible to obtain high rates of germination without the costs of the heat treatment.

7.1.2 Germination under natural conditions

In the semi-wild palm groves, seeds are distributed by a variety of means, human and animal, and become haphazardly scattered through the groves themselves and adjacent forest. Examination of seed in various sites in Nigeria, from high forest to plantations, swampland, palm grove and open country (Rees, 1963b, d), showed

that in the natural forest and grove sites the majority were eaten by rodents or bored into by beetles, or were classed as 'white, delignified' seed. Under grass, about 50% of seed germinated over 140 weeks, and on bare soil more than 20% (Fig. 7.2), but under forest or plantation conditions, no more than about 5% of seeds germinated, and of the remainder more than 80% had been eaten by rodents or damaged by beetles. In all conditions, germination depended markedly on season, taking place only during a short period of about 6–10 weeks, starting about 60 days after the first heavy rainfall of the rainy season.

Rees (1963d) considered that on bare soil during the dry season the seed was effectively receiving a dry heat treatment; a flush of germination thus followed when moisture content was raised by the start of the rains. However, 50–70% of seed stored at high moisture content, but at temperatures similar to those prevailing in forest or plantation, will eventually germinate, although germination is very slow (Rees, 1963d). Thus, where seeds do not germinate at all under natural conditions, this is mainly due to insect and rodent damage, rather than to the lack of heat treatment.

7.1.3 Seed handling

Periasamy *et al.* (2002) illustrated the standard seed handling methods, and also described improvements which led to labour savings of 69%.

7.1.3.1 Preparation of seed

The ripeness of the fruit is not a critical factor in germination (Rees, 1962b). L.H. Jones (pers. comm., 1973) found that embryos dissected out of fruits as young as 70 days from anthesis would grow on a suitable culture

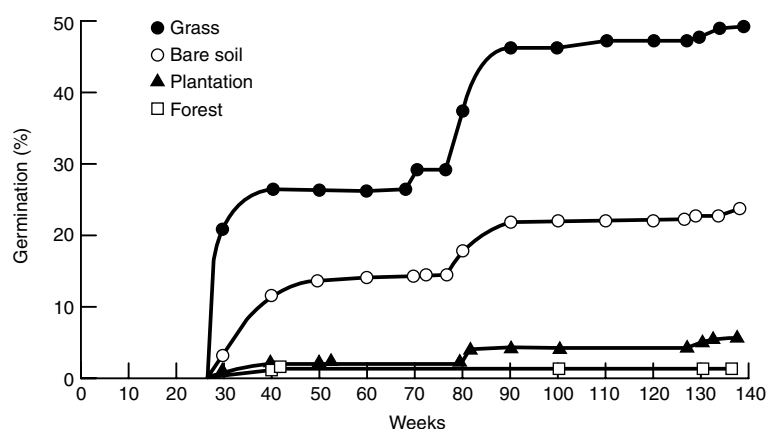


Fig. 7.2 Germination of oil palm seed planted in the open in Nigeria at the end of the wet season (November 1959) until June 1962. (From Rees, 1963d.)

medium. It is convenient to harvest seed bunches before fruit abscission starts, that is, underripe by plantation standards, to avoid any loss of seeds. No differences in germination have been noted between seed from outer fruit and the rather smaller inner fruit (although very small seed often fail to germinate), or between seed of *dura* and *tenera* fruit forms, provided that conditions are appropriate (Hartley, 1988, p. 314). *Tenera* seed may, however, be dried out too quickly if care is not taken. Seasonal differences in germination are not significant, and the age of the seed-bearing palm does not affect germination.

The fruit is first removed from the bunch by cutting off the spikelets and placing them in a gunny sack to allow the fruit to loosen naturally for a few days (this is sometimes incorrectly called 'retting'). The removal of the exocarp and mesocarp from the fruit, usually termed 'depericarping', can be done by scraping with a knife, by soaking in water (true retting), or with a mechanical depericarper. The first two methods are now little used. The mechanical depericarpers most widely used consist of revolving cages of expanded metal mesh, fed with water to keep the fruit wet (for details, with drawings, see Bevan *et al.*, 1966). Escobar (1980) described an improved depericarper which, after the fruit had been retted, removed the mesocarp in about 4 min instead of the usual 30 min. In practice, retting does not appear necessary with this machine (V. Rao, pers. comm., 1998).

Depericarping is followed by drying of the seed to a moisture content suitable for storage (Section 7.1.3.2). Before drying, the seeds may be treated with a fungicide and sometimes a bactericide (Hartley, 1988; Corrado and Wuidart, 1990). The seed is air-dried under shade for 1 or 2 days, and is then ready for storage. With *tenera* seed a shorter period of drying is advocated.

For determination of moisture content, samples should be oven-dried to constant weight. Corrado and Wuidart (1990) recommended a sample of 20 seeds. Mok (1972a) showed that such a sample, from a batch of 1500 seeds, would estimate moisture content to within $\pm 1\%$, with 95% confidence; this appears adequate. To give an estimate within 0.5%, 50–80 seeds would be needed, but such accuracy is probably unnecessary and wasteful of seed. Alizaga *et al.* (1994) described the use of an electric moisture meter with oil palm seed; if sufficiently accurate, this would have the advantage of being non-destructive. Once the moisture content of a batch of seed has been measured, the expected weights at the appropriate moisture contents for storage, heat treatment and germination can be calculated, as a guide for seed handling.

Viability testing with triphenyl-tetrazolium chloride or bromide is widely used as a quality-control method (Mok, 1972b). However, a sample of about 400 seeds is needed to estimate viability with reasonable precision (Mok, 1972a). This is clearly much too large to be practical, and as the smaller samples normally used will only give very rough estimates of the true viability level, it seems unlikely that viability testing serves much useful purpose except, perhaps, for deciding whether it is worth reheating ungerminated seed (Section 7.1.4.4).

7.1.3.2 Storage of seed

Seed physiologists have described seeds that can be dried and stored at low temperature as 'orthodox'. Other species have seeds that do not tolerate drying or cooling, are very difficult or impossible to store, and are termed 'recalcitrant'. This dichotomy is convenient for the managers of seed banks, but is an oversimplification. According to Ellis *et al.* (1991), oil palm, and seeds of some other crops such as coffee, fall into an intermediate category; they tolerate partial desiccation, and can be stored for long periods and at low temperatures, provided that conditions are carefully controlled.

It was noticed by many early workers that the viability of oil palm seed deteriorated gradually, sometimes alarmingly, with length of storage time. However, this appears to have been attributable to poor storage conditions, and later work showed that seed can be stored for long periods (at least 21 months; Rees, 1965b) under suitable conditions. Rees (1963c) observed some loss of viability during 15 months' storage below 14.5% moisture, and concluded that the optimal moisture content for storage was between 14.5 and 22%. Mok (1982) obtained over 95% germination from seed stored for 12 months at 20% moisture, but less good results after storage at 15 or 10%. More recent work has shown that *tenera* seeds can be dried and stored at 7–10% moisture without loss of viability (Ellis *et al.*, 1991), but the method of heat treatment used in this study, described as 'more benign' than the standard method, involved gentle heating for 13 months, so would probably not give the flush of germination over a short period required for a commercial seed operation.

Storage temperature is also important: Rees (1965b) found that storage at 22°C gave good results, but germination was poor after storage at 29°C. Storage of dry preheated seed for more than 2 months is not normally recommended, but Mok and Hor (1977) showed that such seed can be stored for at least 6 months at ambient temperature, with little loss of viability. In summary,

though, it appears that best results will be obtained by storing seeds before heat treatment, at 18–19% moisture (and not below 16%) and 20–22°C.

7.1.4 Methods of germination

There are essentially two germination techniques: the wet heat method and the dry heat method. The former is now little used: the whole process may be shorter (95 days against 120 days for dry heat), but some germination will take place during the heating period and so a less uniform set of seedlings will be produced.

7.1.4.1 Dry heat method

The basis of the dry heat method has been outlined above; it involves heating the seed at a moisture content too low for germination, but not so dry that the heat reaction is impaired. The standard procedure recommended for *Deli dura* seeds (Mok, 1966) was as follows.

1. Ensure that moisture content is 17–18%, soaking to achieve this if necessary. Discard seeds that float.
2. Place seeds in tightly tied polythene bags. Corrado and Wuidart (1990) recommended weighing the

seeds at intervals during the heat treatment, to check that moisture content has not fallen below 17%.

3. Heat at 37–39°C for 50 days.
4. Inspect weekly for mould, and for germinated seeds (germination is rare with the dry heat method, but occasional crosses show a low percentage of germination during heating) (Plates 7.1, 7.2).
5. After heating, soak to bring moisture up to 21–23%. Hartley (1988, p. 322) and Corrado and Wuidart (1990) recommended soaking for 5 days, but Turner and Gillbanks (1974) suggested only 2 days. Too much soaking before germination may be harmful; Ngui and Khoo (1982) showed that germination was lower after soaking for 3 or 5 days than for 1 day. Either a 1 day soak, or 3 days followed by 6 h air-drying, gave satisfactory results.
6. Keep seed in polythene bags at ambient temperature (*c.* 25–30°C); inspect and remove germinated seeds every 5 days. Normally, germination should reach 50% after 15 days and 80% after 30 days (see Section 7.1.4.4 for a discussion of poor germination).

With minor variations in temperature and duration of heating, this method is now used for *dura* seed by all seed producers. A rather higher moisture content of 21.6% during heating has been suggested in Nigeria



Plate 7.1 Small *tenera* seeds having their moisture content adjusted, on inspection, by a fine spray.



Plate 7.2 A flush of germination in a polythene bag, followed the cessation of heat treatment.

(Odetola, 1974a), but there must be a risk of germination during the heat treatment, as this level is close to the moisture content for the wet heat method (see below). According to Rees (1962c) the moisture content during heat treatment, while not critical for final germination percentage, does affect the speed of germination. As Table 7.3 shows, this was fastest at 21% moisture, but some germination occurred during the heat treatment. After heating at lower moisture content, good germination was eventually obtained, but it took longer than after heating at 21% moisture. When seeds were heat treated at even lower moisture content, Rees found that heating was ineffective and germination was poor, but viability of the seeds was not impaired: if the ungerminated seeds were soaked and reheated, most of them germinated.

The optimal duration of heat treatment varies between different genotypes, with Deli *dura* seed generally requiring no more than 40 days (Turner and Gillbanks, 1974), compared with 60–80 days for other *dura* origins. Corrado and Wuidart (1990) recommended 80 days for all crosses. However, prolonged heating of stored seed may slow down germination, and perhaps reduce the final percentage (Fig. 7.3) (Odetola, 1974b).

The requirement for heat treatment is gradually lost during storage, and seed producers typically heat seed

Table 7.3 Effect of moisture content (MC) during heating on subsequent germination

MC after heating	Germination (%) at		Days to 50% germination at optimal MC
	Original moisture	Optimal moisture	
24.2	12	71	23.5
21.3	95	92	6.5
18.6	0	97	17.5
14.2	0	97	25.0

From Rees (1962c).

more than 6 months old for a shorter time than fresh seed. Odetola (1974b) found that seed of one particular cross, after 6 months in storage, gave over 80% germination without heat treatment (this cross may have been atypical, though, as most heat treatments gave 100% germination, which is unusually high). Rees (1962c) estimated, from the Q10 (response to temperature) of germination rate, that 300 days at 27°C should be sufficient to complete the 'high-temperature reaction' (but this is not consistent with a base temperature of 34°C; see Section 7.1.1.1).

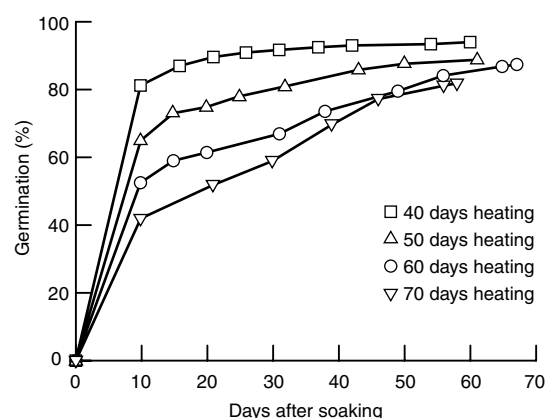


Fig. 7.3 Effect of duration of heating on subsequent germination. Deli *dura* seed, stored for 3 months before heating; figures are means for ten crosses. (From Chew, K. W. unpubl., 1994.)

7.1.4.2 Wet heat method

For this method, the seed must be at the optimal moisture content for germination: 21–22% for *dura* and 26–28% for *tenera*. This can be achieved by soaking the seed for 5 days in water, then drying in the shade for about 2 h, until surface moisture evaporates. The seed is then sealed in polythene bags and placed in the heat chamber at 39°C. Germination will commence during heat treatment, so the seed must be examined twice weekly and any germinated seed removed.

After 80 days the seed are removed from the heat chamber and put in a cool place, with moisture content maintained as before. A flush of germination will start a few days after cooling and should be complete in about 15–20 days. Stored seed requires less heat treatment than fresh seed, so more will germinate before cooling, and the flush of germination of the remainder will not be so pronounced.

If seedlings are urgently required, and there is reason to believe that the heat period requirement may be well below 80 days, the wet heat treatment may be combined with a sampling procedure (Tailliez, 1970). Weekly samples are taken from the heat chamber and kept at ambient temperature. As soon as any such sample has attained 80% germination (this may be expected within 20 days if the heat requirement has been met), all the seed may be taken out of the heat chamber to ambient temperature. The method was devised for use with a wet charcoal substrate, but could also be employed with the polythene bag wet heat method.

7.1.4.3 Germinators

As already noted, the critical requirement to break dormancy, for both dry and wet heat methods, is to maintain a temperature of 37–40°C for up to 80 days. Galt (1953) gave a comprehensive account of the germination methods in use at that time, but most of the germinators, fermentation boxes and pits he described have since fallen into disuse.

For the dry heat method, the requirement for a moisture content too low for germination, but not below about 14.5%, is added to that for high temperature; these conditions can best be achieved by keeping the seed in polythene bags and placing them in a temperature-controlled heat chamber. Electrically heated chambers have proved most satisfactory, with temperature being quite easily maintained within $\pm 1^\circ\text{C}$ (see Hartley, 1988, pp. 317–9, for a description). Some seed producers have installed stand-by generators for their heat chambers, to ensure that temperature can be maintained during a power-cut. This appears unnecessary, as cooling the seed to ambient temperature for 24 h was shown to improve germination (Rees, 1959).

7.1.4.4 Germination abnormalities and problems

In many cases of poor germination a proportion of the embryos is abnormal through incomplete development, malformation, necrosis, or doubling or tripling of the embryo. It has been found that there is a relationship not only between the percentage of abnormality and germination, but also between abnormality and seedling development. Seed lots with more than 15% abnormal embryos tend to give low germination percentages, while the percentage of abnormal and non-developing seedlings will be high. Noiret and Ahizi Adiapa (1970) found a direct relationship between the amount of abnormality and the length and method of pollen storage, and suggested that one cross in five should be examined for abnormalities. They advised eliminating a cross if less than 90% of embryos were normal. If one or more crosses had to be eliminated, then all crosses made in the same month were checked.

Rees (1962b) observed that 'white' seeds, in which the shell is not fully lignified, gave poor germination (only 10% in one test). The seedlings that did develop from such seeds were quite normal, but he recommended that the seeds be discarded because of the poor germination.

Although good overall germination will nearly always be obtained if the heat and moisture requirements are fulfilled, there are factors that may give rise to poor

results. There is evidence of genetic differences in the germination of progenies, some progenies showing consistently poor germination (Henry, 1951, 1952). This is probably less common than was supposed before modern germination methods had been developed, but examples can still be found. From the discussion in earlier sections, possible reasons for poor germination might include:

- low moisture content during heat treatment, perhaps as a result of drying during storage. Ungerminated seed can be soaked and reheated. With stored seed, it is probably safest to measure moisture content, rather than relying on seed colour;
- too high a moisture content during heat treatment; in such a case, some germination during heat treatment may occur;
- too long a period of heating with stored seed;
- too short a period of heat treatment. Corrado and Wuidart (1990) recommended that any seed batches that start to germinate slowly should immediately be returned to the heat chamber for an additional 2 weeks;
- insufficient time allowed for complete germination; some seed producers discard all seed that has not germinated after 6 weeks, but good seed may be discarded as a result. As noted above, a variety of conditions can lead to slow, but eventually good, germination. In germination experiments, treatments have commonly been evaluated over 12 weeks (Odetola, 1974b; Ndon, 1985). A simple practical procedure is to discard seed (or reheat, if the germination percentage is low) when no additional seeds have germinated at three successive 5-day inspections.

7.1.4.5 Germination of *tenera* and *pisifera* seed

Tenera (thin shelled) seeds have been successfully germinated using the wet heat method (Hussey, 1959), but there is little published work on the use of the dry heat method with any but *dura* seeds. [Note that some authors incorrectly refer to the seed from *dura* × *pisifera* (D × P) crosses as *tenera* seed]. Experience shows that *tenera* seed can be germinated by the dry heat method, but individual batches of seed in breeding experiments often germinate very poorly, and the use of the wet heat method might be considered for such seed. With valuable seed it might even be worthwhile excising embryos and growing them initially in sterile culture.

Whichever method is used, *tenera* seed need a higher moisture content than *dura* seed. This is because the saturated moisture content of kernel is higher than that of shell, and *tenera* seeds have a larger proportion of

kernel. Corrado and Wuidart (1990) recommend 20% moisture for heat treatment and 26% for germination of *tenera* seed.

Plant breeders occasionally wish to propagate P × P crosses. *Pisifera* seeds are difficult to germinate because they tend to dry out rapidly, and are susceptible to fungal and bacterial infection. The method developed by Arasu (1970b) gave between 5 and 52% germination of fertile seeds. The percentage of fertile seed varied between parents and between bunches, but rarely exceeded 60%. In Ghana, up to 52% germination of fertile *pisifera* seeds was obtained simply by allowing bunches to lie under the palms during the wet season and protecting them from rodents with wire netting. In this case the mesocarp was clearly giving some protection to the kernel, and the heat requirement was presumably fulfilled by the heat of fermentation (Wonkyi-Appiah, 1973). However, the risk of contamination with illegitimate seed appears high with this method. Note, also, that Rees found that only 5% of seeds on the ground in a plantation survived (Fig. 7.2).

7.1.4.6 Germination of *Elaeis oleifera* and hybrid seed

The germination percentages obtained with *Elaeis oleifera* seed, following the methods used for *E. guineensis*, have usually been low. In Colombia, satisfactory germination has been obtained by heating with 22% moisture content for an initial 15 days, then soaking in warm water at 43°C for 15 min, and following this with the wet heat treatment for 65 days (Chew, P.S. pers. comm., 1976). The method described by Tam (1981) for *E. oleifera* × *E. guineensis* hybrid seed is simpler: heating for 80–100 days at 20–22% moisture, followed by germination at ambient temperature and 22–24% moisture, gave over 70% germination.

7.1.5 Supply of seed to plantations

The number of seeds required to plant a hectare of palms depends on the planting density to be adopted (see Chapter 9) and on the losses at each stage in the process. Assuming a density of 143 palms/ha, Corrado and Wuidart (1990) recommended that 220 seeds/ha be put into germination, assuming that 15% would fail to germinate; Jacquemard (1998), expecting slightly higher losses, recommended 245 seeds/ha. For the same planting density, the advice of Rankine and Fairhurst (1998a) results in a figure of 195 germinated seeds/ha, including a reserve for supplying (replacement after field planting) of 10%.

For sales within the same country, seed producers commonly sell germinated seed. Germinated seed should be despatched as soon as germination has started, and not later than the fourth day, when the radicle and plumule can just be distinguished (see Fig. 2.1d). This enables planting to be done up to 10 days later, when the radicle and plumule are clearly differentiated (Fig. 2.1f, g, Plate 7.3), but not so long that they become twisted. Seed can also be shipped at the end of the dry heat period, with moisture content being adjusted to the optimum for germination on arrival at the destination. This method is probably best when seed is sent from one country to another, but has the disadvantage that the seed supplier has no control over the actual germination process.

Where seed is shipped internationally, the phytosanitary regulations of the receiving country must be observed (see Section 12.1.10). Seed is normally treated with fungicides and insecticides, but germinated seed can be badly damaged by treatment with seed dressings containing certain fungicides or insecticides, and brown germ cannot be controlled by such methods. Gamma-BHC is particularly damaging and should not be used either with seed or in prenurseries. Fumigation with methyl bromide was found to be satisfactory provided the seed moisture content was not more than 10% (Mok, 1970). However, this treatment was done before heat treatment; neither the effect of methyl bromide, nor that of drying to 10% moisture, appear to have been tested after heating.

Locke and Colhoun (1973) showed that *Fusarium oxysporum* f.sp. *elaedis*, the pathogen of vascular wilt disease, could be seed-borne, and Flood *et al.* (1990) found pathogen spores on the kernel surface, inside the shell. Dossa and Boisson (1991) showed that *F. oxysporum*

from wilted oil palms in Brazil was closely related to strains from the Ivory Coast, and it seems likely that the Brazilian outbreak arose through seed transmission of the pathogen. These studies showed that the current methods of disinfection were inadequate and that more stringent procedures were required. Flood *et al.* (1994) developed a method of fungicide treatment involving vacuum infiltration, which kills fungal spores inside the shell, on the kernel surface, as well as on the outside of the seed. This treatment should become routine whenever seed is shipped from one area to another.

7.2 NURSERIES

Growth of seedlings is described in Section 2.2.1.2 and the possibilities of selection at the nursery stage are discussed in Section 5.2.7. Early bearing in the field is dependent on the transplanting of healthy seedlings from a nursery. Direct planting of germinated seed or very small seedlings in the field is possible but is not a practical method, as losses are heavy and growth is uneven (Hartley, 1988, p. 239). A great deal of attention has therefore been paid to nursery techniques, and various systems were developed in different parts of the world in response to differences in climate, soil, disease incidence and management (Jacquemand, 1998; Rankine and Fairhurst, 1998a; Duckett, 1999). All nursery systems called for the minimum disturbance of the roots throughout the nursery period and during transplanting to the field.

Seedlings are harder to raise in the seasonal climate of Africa than in the more uniform climate of the Far East and they are much more subject to nursery diseases.



Plate 7.3 Planting a germinated seed in a sand-bed prenursery.

At first, therefore, more research was done on nursery methods in West Africa than elsewhere, but the method of raising seedlings in large polythene bags, developed in the Far East in the mid-1960s, has become universal. There are two possible methods, the single-stage main nursery, and the two-stage method, with prenursery and main nursery. The main advantage of the single-stage nursery is a reduction of overall time in the nursery by about 2 months (Bevan and Gray, 1966). Omitting the prenursery stage and planting germinated seed direct into large polybags gave larger seedlings on transplanting to the field at 13 months from germination than were obtained from using prenurseries, but this effect did not persist for more than a year in the field (Hew and Tam, 1969). This has to be set against higher labour and water requirements in the first 4 months, the need for closer supervision at the initial stage and a larger total area (Rankine and Fairhurst, 1998a).

7.2.1 The prenursery

Prenurseries may be planted in polybags, 'Malacca' cane baskets or beds, but polybags are now usually used. Chee *et al.* (1997) advocated reusable plastic trays, each holding 24 seedlings. Germinated seeds are now the standard planting material, but in the past, seedlings at the two-leaf stage were sometimes sent from a distribution centre as bare-rooted seedlings packed in polythene bags; handling of such material is described by Hartley (1988, p. 330).

7.2.1.1 The polybag prenursery

The setting out of a polybag prenursery is described in detail by Rankine and Fairhurst (1998a) and IRHO (1986a, b). Bags holding about 1.5 kg of soil are usually used. In general, a fertile, well-structured topsoil, sufficiently free draining to prevent 'puddling' or sealing of the surface, is required. With heavy soils, the admixture of a proportion of coarse sand is desirable, unless it causes the soil to break up on transplanting to the main nursery (Hartley, 1988). The germinated seed is planted about 2.5 cm deep; planting deeper than this delayed early growth slightly (Tan and Mohan, 1982). Care must be taken to ensure that the plumule is pointing upwards and the radicle downwards (Plate 7.3); twisted seedlings are thus avoided.

7.2.1.2 Maintenance of the prenursery

Shade: Shading of the prenursery may not be required if overhead irrigation is supplied, or when hand watering

is adequate and efficient, but direct sunlight can cause overheating and damage to the leaf, and it is safer to provide shade. The aim is to reduce normal light intensity by about 60% initially, removing the shade progressively over a period of 2 weeks, commencing 10 weeks after planting (Turner and Gillbanks, 1974).

Mulch: The primary requirements for maintaining a steady growth after emergence of the first leaf are adequate watering and a balanced supply of fertiliser. Mulched seedlings grow better in the nursery (Dupriez, 1956; Gunn *et al.*, 1961). The most satisfactory mulching material is finely divided bunch refuse; this may be applied soon after planting. Alternatively, sawdust, palm shell, groundnut husk or other fibrous material may be used.

Watering: Provided the soil used is not too heavy and drainage is unimpeded, there is little danger of overwatering. In severe dry weather, twice-daily watering to 'run off' will be needed, equivalent to 0.2–0.3 litres/seedling (Turner and Gillbanks, 1974). Hand-watering may be suitable for a small nursery, but is inevitably uneven, and in any permanent prenursery site an irrigation system should be installed (Plate 7.4). Bevan and Gray (1966) considered that irrigation equipment was justified for field plantings of 400 ha or more.

Fertiliser: Although, as already noted, the seedling obtains much of its needs from the endosperm, in most soils prenursery seedlings have shown marked responses to fertiliser. Experiments in Nigeria and Malaysia have shown responses to nitrogen and phosphorus, particularly as ammonium phosphate, but not to potassium. The amounts required are very small (Hartley, 1988). If fertile forest topsoil is used for the prenursery, fertiliser application may not be needed, but such soil is often unobtainable and its use should be discouraged from a conservation viewpoint.

Weeding: Since seedlings are in the prenursery for only 3 or 4 months, very little weeding is normally required and hand-weeding is usually adequate. In the Ivory Coast, it was claimed that application of a pre-emergent herbicide such as ametryn would reduce costs to 10% of those of hand-weeding (Taillez, 1969). This herbicide could be applied before the emergence of the plumule, or at a lower concentration after the emergence of the plumule but before the appearance of the first leaf.

7.2.2 The main nursery

Field nurseries, where palms are planted in the ground at close spacing, and uprooted for transplanting later, are described by Hartley (1988, pp. 337–9), but are no longer used. To avoid transplanting shock, it was essential to



Plate 7.4 Large polythene bag prenurseries under irrigation in the Jengka Triangle area, Pahang, Malaysia.

maintain a ball of earth around the seedling roots, but with most soils this was very difficult. Gray, in the Far East, introduced large black polythene bags filled with friable topsoil, and showed that, with heavy watering, healthy seedlings could be produced (Plates 7.5, 7.6). He also demonstrated that it was possible to dispense with the prenursery stage by planting germinated seed straight into the large polybag (Bevan and Gray, 1996).

Polybag and field nurseries were compared in both Malaysia and Nigeria. In Malaysia, there were no significant differences between polybags and field nurseries, in either palm growth or early bunch yield, but the survival rate was slightly higher with polybag palms (Hew and Tam, 1969). In Nigeria, polybag plants showed slower growth in height than field nursery plants, but they had a lower blast incidence and produced more leaves, and more seedlings were adjudged transplantable. On planting into the field the polybag plants showed more rapid initial growth, and after 18 months were significantly taller and had produced more leaves (Aya, 1974).

7.2.2.1 The polybag nursery

Nursery methods were described by Quencez (1982) and by Rankine and Fairhurst (1998a). Various sizes of polybag have been used, but the usual size, 50×38 cm or 45×40 cm, contains about 16 kg of soil. Palms to be held back in the nursery for supplying (replacing of losses after field planting) should be planted in larger bags (Rankine and Fairhurst, 1998a).

Soil-sand mixtures should be similar to those used for prenurseries. The addition of cattle manure has



Plate 7.5 A polybag plant about 75 cm high, 4–6 months before field planting. Bag 38×50 cm (lay-flat).



Plate 7.6 A large polythene bag nursery in Malaysia.

been shown to improve growth in the bags (Hartley, 1988). It is generally recommended that the bags are filled at the source of soil and then transported to the nursery as this entails less handling of soil than filling at the nursery site, but an alternative system developed in Ghana looks particularly good. For this method, a permanent nursery site is needed, twice the area required for one year's planting. One half of the site is used in the first year, the third year, and so on, while the other half is used in the alternate years. Soon after transplanting seedlings from the prenursery, the area between the bags is mulched with a layer of empty bunches (EFB), using about 450 t EFB/ha. Once the palms have grown and been removed from the nursery, the EFB is left to decompose for a further year, before the area is rotavated. The bags for the third year's nursery are then filled *in situ* with a mixture of soil and decayed EFB. This method involves no soil transport and almost no weeding costs, and palm growth is excellent. Moisture retention in the bags is good, and the bags are relatively light to handle at planting time (B. Ghansah, pers. comm., 2001). The only problem is seepage of polluted water from the decaying EFB. Care must be taken to drain this into an adjacent field, avoiding contamination of any water course.

In Malaysia, a spacing of 90 cm triangular is recommended in the main nursery; where an irrigation system is in use the bags may be placed at this spacing from the start. With hand-watering the bags can be placed close together in rows three bags wide until the seedlings are about 6 months old from germination;

they are then separated to 90 cm. Closer spacing (70 cm triangular) has been recommended (Quencez, 1982), but may cause etiolation of larger plants towards the end of the nursery stage.

With a two-stage nursery system, prenursery seedlings at the four- or five-leaf stage, 10–14 weeks from germination, will be transplanted. The prenursery bag is cut or torn off, the seedling with its ball of soil inserted in a hole dug in the soil in the large bag, and the soil consolidated around it. The soil surface from the prenursery bag should be levelled with the surface in the larger bag; Tan and Mohan (1982) found that deeper planting slowed down growth and development.

In a single-stage nursery, with direct planting of germinated seed in large polybags, methods are the same as for the prenursery, but some shade is usually required until the one- or two-leaf stage is reached. The system may be more expensive in labour and water in the first 4 months than the two-stage nursery, but this disadvantage is outweighed by a reduction of about 2 months in overall time in the nursery (Bevan and Gray, 1966).

7.2.2.2 Time of planting

In seasonal climates and in areas subject to blast disease, the time of planting a nursery is very important. Elsewhere, nurseries may be laid down at any time of year, although it is preferable to choose a period when rain is most likely to fall and which allows a lapse of 12–16 months before the prearranged field-planting

programme. Both in the Congo and in the Far East nurseries are commonly planted all year round and nursery plants are taken for planting in the field in the wetter periods, beginning in April or September.

In West Africa the field-planting season runs from the beginning of the rains, in March, until May or early June, so nurseries are planted early in the previous year. In the Ivory Coast, where the rainfall is more uniform than in other parts of West Africa and completely dry months are rare, April is also preferred for field planting, even though the short dry season of August and September is more pronounced than elsewhere and October and November rainfall is high.

Early planting of nurseries is desirable in Africa for the avoidance of blast disease (Section 12.1.4). In Nigeria, April to June was the best period for establishing a field nursery from pre-nursery seedlings, giving the least blast and the highest number of transplantable seedlings at field-planting time a year later (Gunn *et al.*, 1961). These findings were largely confirmed for poly-bag nurseries with the direct planting of germinated seed. Aya (1979) found that from mid-April to mid-May, i.e. early in the rains, was the best time for establishing a nursery, giving a lower blast incidence and better development up to 10 months than establishment either earlier or later.

Blast disease in Nigeria tends to attack small seedlings, and usually only between the months of October and January. Very small seedlings planted in October and shaded are not susceptible, and for this reason a 'dry-season nursery' planted in that month was tried in Nigeria (Gunn *et al.*, 1961). This nursery could be brought forward by irrigation, mulching and more frequent fertiliser dressings so that seedlings become transplantable in late May, when 70–100 cm high. This is not, however, the optimum size or age for transplanting, and Aya (1979) concluded from his polybag experiments that, although dry-season nurseries are feasible, the resulting seedlings would not be of transplantable size at the right time.

In South and Central America there is a great variety of seasonal climates. In northern Colombia, for instance, the dry season is at much the same time of year as in Nigeria, and both transplanting to the field and nursery establishment are therefore best done in March to May. On the Pacific plain of Ecuador, in contrast, the long low-rainfall but cloudy period ends in November to December, and both field and nursery planting are best done then, before the rains of January to April set in (Hartley, 1988, p. 346).

To summarise, in planning germination and nursery work, timing should be calculated back from the

planned time of field planting, as follows:

	Two-stage nursery with pre-nursery (months)	Direct planting in main nursery (months)
Germination (dry heat treatment)	3–4	3–4
Pre-nursery	4–5	–
Main nursery	10–12	12–14
Total	17–21	15–18

Thus, if planting is planned to run from September to November, germinated seed should be ordered to arrive in batches from April to July of the previous year for a pre-nursery, or from July to September if there is to be no pre-nursery.

7.2.2.3 Nursery maintenance

Irrigation: Rees and Chapas (1963b) measured water consumption by seedlings in a field nursery, and found a maximum, during the dry season, of about 150 mm/month. The water requirements of polybag nurseries have been variously estimated; most authorities arrive at an overall requirement figure of between 6 and 8 mm/day (Turner and Gillbanks, 1974; Gilbert, 1979), but Quencez (1982) considered the requirement to rise with age, reaching 10 mm/day by 6–8 months. The actual amount applied should supplement rainfall up to these figures (calculated based on the total area of the nursery, not of the polybag surface).

The water needs can be more accurately and economically supplied by an overhead irrigation system than by hand-watering. Although water consumption should be less with hand-watering, since the water will be applied only to the soil in the bags and not to the whole area, hand-watering is often difficult to supervise, and the application rate may be higher than the infiltration rate, leading to overflow and wastage. The soil surface needs to be mulched, or disturbed from time to time, to prevent capping.

The construction, layout and operation of irrigation systems for oil palm nurseries have been described in detail by Bevan and Gray (1969), Gilbert (1979) and Quencez (1982). Systems may be of the large rain-gun type, needing pressures of around 7 kg/cm², and supplying 25 mm/h, or the smaller rotary sprinkler type, requiring lower pressures (1.5–3 kg/cm²) and supplying 2–11 mm/h. An alternative is the sprinkler tube; this consists of lay-flat plastic tubing, with two rows of holes on the upper surface (Ramli and Duckett, 1988); these give a fine

mist to a height of about 2 m. This system is much cheaper than polyvinyl chloride (PVC) or metal piping and sprinklers, is easier to set up and requires a water pressure of only 0.5 kg/m². Lim and Ho (1993) compared sprinkler and drip irrigation, and found the latter to give more uniform and better growth. Water consumption was lower with drip, because water was supplied only to the bags, and not to the whole nursery area.

Shade: Shading of the main nursery is not required except as an anti-blast disease measure (see Section 12.1.4). In West Africa it was noticed that plants shaded through the dry season increased more rapidly in height, but later, when the shade was removed and the rains had set in, they grew more slowly than unshaded plants (Gunn and Sly, 1961).

In a single-stage nursery, some shade is usually required until the one- or two-leaf stage is reached. This can be supplied most economically by bending palm leaflets over the developing seedling and pushing them into the soil on each side of the bag.

Weeding and mulching: Nursery weeding is usually carried out by hand. Monthly weeding rounds are recommended in Malaysia for both the bags and the intervening ground (Bevan and Gray, 1969). Rankine and Fairhurst (1998a) recommended the use of a gramoxone-diuron mixture for the ground between the bags, but emphasised that the bags should be weeded by hand, to avoid any risk of herbicide damage to the palms.

Mulching of the soil surface in the polybag may be done with bunch fibre, or with shell, and the amount of weeding required should not be very great. Quencez (1982) recommended treatment of the area with a pre-emergent herbicide such as ametryn, before the bags are positioned. This treatment can be repeated later, provided care is taken to avoid spraying the palms.

Fertiliser: Polybag nurseries may be fertilised with straight or compound fertilisers. Detailed recommendations are given by Quencez (1982), Rankine and Fairhurst (1998a) and Turner and Gillbanks (1974). Precise requirements will depend on the soil used, but the main requirement in the nursery is for nitrogen. Studies have been done with slow-release fertilisers in the nursery, the expectation being that a single application, at the time of transplanting to the main nursery, may be sufficient. In practice, though, growth has usually been slower with these compounds than with a conventional fertilizer programme (e.g. Lim and Chan, 1993; Sidhu *et al.*, 2000).

7.2.2.4 Culling and nursery abnormalities

At each stage in the nursery, there will be losses due to pests, disease or accident, and also some abnormal

plants which should be destroyed. Expected losses at each stage are 10–15% at the end of the prenursery and 10–20% at the end of the main nursery (Jacquemard, 1998; Rankine and Fairhurst, 1998a; Corrado & Wuidart, 1990).

In the prenursery, there may be a small percentage of genetically stunted or abnormal seedlings, but the majority of slow-growing or abnormal plants are probably the result of cultural deficiencies, usually bad planting (seed too deep, or inverted) or insufficient water. Plants suffering from twisted growth, or showing symptoms of leaf roll, leaf crinkle or collante (see Section 12.1.2.2), should be removed, as should those which show poor development, abnormally erect or dumpy habit, or very narrow 'grass leaves'.

The question of culling from the main nursery has been given much attention. The types of abnormality that should be culled were listed by Tam (1973), who showed that yields of these palm types ranged from zero up to about 63% of 'normal' palms, with rotten bunches very common from some types. The potential losses, if such palms were to be planted, make it essential that they be eliminated. Culling can be conveniently done at 8 months and it should then be necessary to discard very few plants at transplanting time. The abnormalities, most of which were illustrated by Rankine and Fairhurst (1998a), are listed below, together with the expected yield shortfall over the first 2 years, for the types recorded by Tam (1973):

- unusually upright and narrow with height greater than width (yield loss of 92–100%)
- flat-topped, with successively shorter leaves giving a bunched appearance (51% loss)
- spread out with flaccid, curved leaves, also giving a flat-topped appearance (41% loss)
- maintaining a juvenile type of growth, although large, so that the leaves do not become fully pinnate (88–100% loss)
- leaflets inserted at an acute angle to the rachis, i.e. 45° or less instead of 60–90°. Tan (1975) showed that such palms yielded between 62 and 77% less than normal palms over the first 4 years of production; Tam (1973) recorded a loss of 70%
- unusually narrow leaflets, rolled longitudinally to give a narrow appearance (87% loss)
- unusually short but broad leaflets which come to a point abruptly
- leaflets tending to be crowded together and often short and crimped (73–96% loss)
- leaflets much wider apart on the rachis than usual (87% loss)

- yellow or white stripes or patches on some of the leaflets
- cases of collante and leaf crinkle, which can occur in the main nursery as well as the prenursery.

It is possible to raise both seedlings from double seeds (Rankine and Fairhurst, 1998a), but it is generally regarded as sounder practice to discard one, retaining the other with the seed attached.

A normal polybag plant at 8 months has been described as having a height of 0.6–1 m, a girth of 18–22 cm and seven or eight functional leaves (Jacquemard, 1998), but there is no case for heavy selection on the basis of height or size of plants. Differences in height of palms of the same age in the nursery tend to even up when the plants are transferred to the field. This was particularly true of field nurseries, where Sparnaaij (1955) observed that differences in nursery growth were predominantly environmental. In a polybag nursery, the environment is more uniform, and genetic differences are probably more obvious. Individual progenies may show very different conformations and rates of growth in the nursery, so in a mixed lot of crosses, many plants will be relatively short because this is a characteristic of their parentage, rather than because they are abnormal. Where several different origins are planted in the same nursery, it may be sensible to keep the origins separate, so that differences attributable to parentage are obvious.

7.2.3 Advanced planting material

Advanced planting material (APM) consists of palms that have been allowed to develop further in the nursery than normal, with the aim of shortening the non-productive, immature period in the field. An APM nursery requires specific planning; palms held in the nursery for longer than normal at standard spacing simply become etiolated and root-bound, and the immature period is not reduced (Hashim *et al.*, 1988a). Nazeeb *et al.* (1988) and Chinchilla *et al.* (1990) showed that best results were obtained by using large bags at wide spacing, and that only a slight extension of the time in the nursery was then necessary.

Bags of 60 × 75 cm, at a spacing of 1.8 m triangular, are recommended (Rankine and Fairhurst, 1998a). These are very heavy, and mechanical handling may be required. Hashim *et al.* (1988b) suggested mixing 75% (by volume) of expanded polystyrene granules with the soil, to reduce weight. The granules hold little or no water, so the soil must be chosen with care and watering must be very regular. Good results, in terms of nursery

growth, were obtained, but the palms had a tendency to blow over in the wind. However, Nazeeb *et al.* (1993) found that growth was poor with polystyrene granules. Umaña *et al.* (1990) obtained the best growth in soil, compared with soil/mesocarp fibre, soil/shell or soil/rice husk mixtures.

The use of APM is discussed further in Chapter 9.

7.2.4 Nursery pests and diseases

Diseases of oil palm seedlings are described in Chapter 12, but as they have had an influence on nursery practice some mention of them should be made here. Perhaps the most important point to emphasise is the importance of nursery management in minimising disease susceptibility. With adequate water supplies and balanced nutrition, nurseries in many areas remain largely free of serious diseases, and investigations into disease outbreaks may primarily involve examination of growing techniques, rather than a search for a pathogen (Turner, 1981).

Blast disease in West Africa normally attacks young seedlings between October and January, from the end of the rains until well into the dry season. It has been shown that:

- seedlings of 1 year or more old are rarely attacked (Bachy, 1958);
- seedlings planted in October and shaded escape attack (Gunn *et al.*, 1961);
- the severity of the 'short-dry' season of August affects the incidence of blast, and hence the provision of irrigation water during this season reduces blast incidence (Robertson, 1959a).

Shade was regarded as the only protection against blast until the role of the homopteran, *Recilia mica*, in transmission of the disease in the Ivory Coast was discovered (Quencez, 1982). It still remains unclear whether blast has the same cause all over West Africa; in Nigeria, Robertson (1959b) was able to cause symptoms by inoculation with fungi (see Section 12.1.4). In general, though, shade as a method of control has been abandoned in favour of systemic insecticides.

Pests are more troublesome in nurseries in Asia and America than in Africa, and while regular prophylactic spraying is not usual, a close watch must be kept for snails, night-flying beetles (*Apogonia* and *Adoretus* species), crickets and grasshoppers, and leaf-cutting ants, and spraying must be started as soon as necessary. In the prenursery, these pests can usually be controlled by hand collection.

7.2.5 Nursery costs

Detailed costs of polybag nurseries in terms of man-days have been given by Quencez (1982) for Africa and by Bevan and Gray (1969) for Malaysia, for two-stage nurseries. Rankine and Fairhurst (1998a) gave recommended task sizes for most nursery operations. Quencez estimated that 1 ha of nursery, at 70 cm triangular spacing and including paths, would hold 18,000 seedlings, sufficient for 100 ha of field planting at 9 m triangular. Labour usage per hectare of nursery was 1815 man-days, so the labour requirement was 18 man-days/ha of plantation, or 126 man-days/1000 transplantable seedlings. In 1982 labour made up 46% of the total cost of the nursery.

With the recommended Malaysian spacing of 90 cm triangular, 1 ha of nursery holds about 11,000 seedlings, so labour use per hectare of field planting might be expected to be higher. Hartley (1988, p. 351)

quoted a mean figure for Malaysia of 24 man-days/ha, or 168 man-days/1000 transplantable seedlings, but the data in Bevan and Gray (1969) indicate only about 12 man-days/ha of field planting.

Prenursery labour costs are very small, amounting at most to 4 man-days/ha of field planting (Ruer, 1963), and perhaps as little as 1.5 man-days (Bevan and Gray, 1969). Taken together, prenursery and nursery costs make up only about 7% of the total cost of bringing a planting into production (Donough, 2002). Thus any attempts at cost saving which risk reducing the quality of the transplanted seedlings are misplaced, as they may be followed by reduced yield. Donough (2002) emphasised the importance of thorough culling in obtaining good yields, and pointed out, even if culling rate were increased to 50%, planting material would still make up only 10% of the capital cost of a planting.

Chapter 8

Site Selection and Land Preparation

8.1 CHOICE OF SITE FOR OIL PALM PLANTING

8.1.1 General

There are many general constraints on the choice of planting sites, including commercial availability of land and labour, transport routes, and political and financial stability. The constraints discussed here are those that determine technical success in yield and management, i.e. soil type, climate and slope. The last of these is fairly obvious on inspection, but soil type is not, and a professional soil survey, by specialists who are familiar with the area and the oil palm, is essential before any commitment is made. The main climatic factors are fully as important, and data for the locality must be available for a sufficiently long time to give dependable average values, and the frequency of recurrence of extreme events such as violent storms or extensive droughts. The choice of a good site is critical, because the plantation will continue for at least one, and probably many more planting cycles if it proves successful, but it may rapidly prove to be uneconomic if placed on the wrong site.

8.1.2 Climate requirements

These have been outlined in Chapter 3. It must be remembered that the range of latitudes at which oil palms can be grown commercially differs from continent to continent, because the global oceanic and atmospheric currents affect the climate. The presence and relative position of large land masses also greatly modifies the temperature and rainfall (Ollagnier *et al.*, 1970). The requirements are obviously dependent on the expected general yield level in a particular country. Some reported yields that are considered reasonable are given in Table 3.9. The relatively poor results with both very high and very low rainfall are evident. A more detailed set of climatic requirements is given in

Table 3.10. This suggests that the best yielding oil palms need, as a minimum:

- adequate sunshine hours and solar radiation of 16–17 GJ/m² per day
- rainfall of 2000–2500 mm, uniformly distributed
- low vapour pressure deficit, with no extreme temperatures or wind speed.
- temperatures of mean maximum 29–33°C and mean minimum 22–24°C.

Climatic conditions usually preclude planting much above 200 m above sea level, although palms can survive at well above this (Hartley, 1988) (Section 1.2.1). Ideally, all of these criteria are met; the problem lies in deciding on the acceptability of a site where one or more of the criteria is not perfect. At present this can be done only by prior experience and general inference, even when this is built into a semi-quantitative system such as that of Paramanathan *et al.* (2000) (Section 8.1.5). With the increasing probability of climate change (IPCC, 2001) and the lack of any good predictions of what this may involve in particular localities, it is important not to accept sites with marginal climate properties, but to require sites with average climatic factors. For these some degree of change will be acceptable in the future. Ultimately, the need for site assessment may be met by whole-crop models of the oil palm that include both the climate and the soil properties of an environment. However, these will need to have been very well verified before risking large sums on planting up areas with suboptimal climatic conditions.

8.1.3 Soil type requirements

The soil types generally used, and the soil types that cause problems in use, are discussed in Chapter 3. A more detailed consideration, with practical guidance on soil sampling, recording and analysis, is in given Paramanathan *et al.* (2000), which sets out all of the major factors that limit oil palm cultivation. The following factors need special consideration.

8.1.3.1 Intensity of soil survey needed

This depends on the complexity and variability of the soil, the degree to which all local soil types are suitable for oil palm, and the amount of prior knowledge of the area in question. Thus, a reconnaissance soil survey, with traces at 2 km intervals, is suitable for a first check on the area, but later a semi-detailed survey with 1 km traces may be desirable. A more detailed survey using existing roads and paths may be made after the area is planted, as a guide to management. If earlier work has allowed the suitability of recognised soil series for oil palms to be defined with some certainty, a simple soil survey may provide sufficient information. This situation is certainly true in Malaysia and Indonesia. It may also be the situation in Sri Lanka, where Kalupahana and Mapa (1997) have evaluated the relevant soil series. From the surveys, information about the following points must be obtained (Hartley, 1988; Paramanathan *et al.*, 2000).

8.1.3.2 Topography

This aspect, as with the survey, needs good maps, including contour information, which can now be used with digital terrain maps (DTM), Global Positioning Systems (GPS) and Geographical Information Systems (GIS) where these are available (see Section 10.7.5). Rankine and Fairhurst (1998b) recommend no planting above 40° and that platforms are sufficient up to 20° (38%), but Hartley (1988) and others considered that 20° should be the final upper limit. Plantations exist in Sabah and Kelantan on slopes of up to 30° (60%) (Section 8.3.5), but harvesting is difficult and there is always a danger of erosion. Palms should not be planted on slopes over 20° (38%), although it is best not to exceed 12° (23%). On broken land, the variation of slope makes road layout difficult, as road density needs to be high because of the difficulty of in-field transport. It also causes variation in light levels and wind effects. The expected progressive increase in mechanisation must also be considered when proposing to plant steep slopes. This means that in-field transport will have to be able to travel along terraces, and this adds greatly to the complexity of the layout and makes it difficult to use slopes of above 6° (Section 8.3.5).

Kee and Soh (2002) summarised much of the earlier information. They identified the problems with slopes as the need for planting and/or conservation terraces, ground cover care and mulching with EFB. All are well known, but are often ignored because of the expense. Surface runoff of fertiliser is possibly the worst problem. They concluded that planting should not be done at all above 25° and that there were increasingly serious

problems from 16° upwards. This is probably close to the average opinion at present.

Hilly land also often has shallow soils or very variable depths with position on the slope. Hamdan *et al.* (2000) showed that cutting terraces into saprolite (rotten rock) on a steep slope reduced the average quality of the soil for the palms planted there. There will often be problems with standing water because of the backward slope of terraces. Even on moderate slopes of say 12°, soil conservation measures (terracing, platform building and stacking cut fronds in lines along the contour) will still be necessary, depending on the soil texture and structure. Some soil/terrain combinations are so prone to erosion that they would not be considered for planting in any circumstances (Gobin *et al.*, 1999). Hartley (1988) favoured individual palm platforms, but in practice terraces have to be used to provide harvesting paths above 12° slope. The problems of terracing or platforming on steep slopes are discussed later.

8.1.3.3 Rooting depth

A rooting depth of at least 100 cm is desirable, preferably more, although palms will grow with only 50 cm rooting depth if their needs for water and physical support can be met. Possible impediments are dense layers of lateritic or other gravel, solid rock or unfavourable chemical conditions, e.g. the acid sulfate soils (see Section 3.4.3.3). As an example, Adiwiganda *et al.* (1993) reported that in Riau province in Indonesia a tract of nearly a million hectares was surveyed, in which most of the soils were spodosols (tropical podsols). They contained a spodic (organic matter and iron accumulation) horizon between 40 and 80 cm that prevented root penetration. The overlying albic (heavily leached) horizon was of very low chemical fertility, and hence the soil was assessed as being of no value for oil palms. A restriction in rooting volume can lie either in the shallow depth of soil available above an impenetrable layer, or in the very small fraction of true soil in a deeper but gravelly profile. Thus, palm roots can penetrate gravelly layers, even if they become distorted and misshapen, but gain very little useful water or nutrition thereby, unless the true soil is very fertile and water retentive.

Rey *et al.* (1991) produced maps of soil quality, paying special attention to rooting depth and water supply. In the deep acid sands of West Africa they found (see Section 11.2.1.1) tertiaries and quaternaries down to 450 cm, and water was absorbed down to at least 5 m. The average available water was 250 cm, of which 116 cm was in the top 2 m, and the remaining 134 cm was in the 3 m of soil below. The paper did not, however, consider the rate at which water is required and

can be extracted from these depths, which may be just as important as the absolute amounts present.

It is rather unusual to ameliorate a physical constraint at depth, but Caliman *et al.* (1990) found that subsoiling before replanting sandy ferrallitic soils on savannahs in the Ivory Coast loosened a compacted horizon that had formed since the first planting (see Section 3.4.3.1). In a large field experiment they showed that this treatment produced a more extensive and deeper root system, and better vegetative development. The permanence and the economic profitability of such treatments need to be determined. Great attention is also paid to soil compaction in Costa Rica.

8.1.3.4 Moisture availability

The need for high available water capacity in the soil (e.g. 200 mm, see Chapters 3 and 4) has to be assessed against the distribution of rainfall. In a highly seasonal climate this is extremely important. Available water content of soil profiles depends on the porosity distribution. Very fine pores, as in a massive clay, are of little use because water is held at too high a suction, whereas large pores will empty rapidly under gravity. The intermediate size pore space fills and empties between field capacity suction (ca. 10 kPa) and permanent wilting

point (1.5 MPa suction), although water held at greater than 100–200 kPa suction will only be extracted very slowly. (Water potential is measured in 1 MPa = 10 bar.) The pore size distribution is a complicated function of the texture, the structure and the history of the soil (White, 1997). Very sandy soils have little available water, and when such soils were planted in Kalimantan produced very poor results (Paramanathan, 2000a). Ideally, the information for a full water balance should be available (Kee *et al.*, 2000), as this can be related to the effects of the field capacity and the critical deficit (3.2.2.3). This allows different sites to be compared in a reasonably exact way (Table 8.1).

8.1.3.5 Soil fertility

Nutrient content can, in principle, always be ameliorated with fertilisers. This is particularly so for a perennial crop, because the plant itself has large nutrient reserves, so that the exact time or place at which fertiliser is applied is less important than for annual crops (see Section 11.9.3). Nevertheless, heavy fertilising is an additional expense, and the use of nitrogen carries problems in high-rainfall areas (see Section 11.7.4.1). If an inherently fertile soil is available, it clearly has management advantages over an infertile one. Soil analysis

Table 8.1 Annual water balances for two sites in Peninsular Malaysia and one site in Sabah, estimated from monthly data of rainfall, runoff and evapotranspiration between 1992 and 1996 (see Table 3.9)

	Balau Estate (Semenyih, Selangor)		Lepan Kabu Estate (K. Krai, Kelantan)		Sri Kunak Estate (Tawau, Sabah)	
	(mm)	(%) ^f	(mm)	(%) ^f	(mm)	(%) ^f
Palm age (years)	17–22		18–23		13–18	
Mean annual precipitation	2,527	100	2,648	100	2,060	100
Intercepted rain ^a	701	28	723	27	637	31
Throughfall ^a	1,596	63	1,682	64	1,247	61
Stemflow ^a	229	9	243	9	176	8
Runoff ^b	751	30	851	32	452	22
In trunk and in FFB crop ^{c,g}	12.7	0.5	10.7	0.4	12.8	0.6
Est. evapotranspiration ^d	1,498	60	1,050	40	1,339	65
Est. annual deficit	28		115		49	
Est. surplus (percolation)	278		747		288	
Nett surplus ^e	265	11	736	28	275	13

After Kee *et al.* (2000).

^a Daily rainfall partitioned, totalled over each month and year, then averaged over 5 years.

^b Annual runoff mean over 5 years.

^c Annual increment of water storage in trunk and removed in FFB crop.

^d Estimated $E_a = (E_0 - \text{deficit})$; E_0 based on pan evaporation with crop coefficient of 1.

^e Net surplus = (Percolation – water immobilized in trunk and exported in FFB).

^f Percentage of annual precipitation.

^g Based on 24, 20 and 26 t FFB/ha per year, respectively.

should be used extensively in this assessment of soil characteristics before establishment of the plantation, although it is rarely used as a tool during the actual management.

8.1.3.6 Soil sustainability and long-term changes

A plantation is expected to continue for up to 25 years, and it may then be replanted with the same crop an unknown number of times into the future. It is important to be certain that the soil properties are stable, i.e. that any progressive soil change does not damage the plantation's productivity, just as it is important to consider the question of climate change.

The most obvious soil problem is erosion. This can occur in various forms e.g. splash erosion arises because the raindrops have enough energy to disaggregate soil structure (Fig. 8.1) (White 1997) and soil is moved downhill by the splash. More generally, when the rainfall is large enough to cause surface runoff, then surface wash, sheet erosion or gully erosion occur (Lim, 1990; White, 1997). On steep and long slopes surface flow rapidly builds up under heavy rain (Maene *et al.*, 1979). Erosion is very dependent on vegetation cover, and with well over 2,000 mm rainfall in many palm plantations, the effect of vegetation is critical. Erosion can be serious in early years, with an incomplete palm canopy, unless a cover crop is rapidly established. The leguminous cover, which should be established as soon as possible, is the main protection against erosion, but in sloping land terraces and bunds, made of soil or palm fronds, are desirable to interrupt this flow (Lim, 1990) (Section 8.3.5).

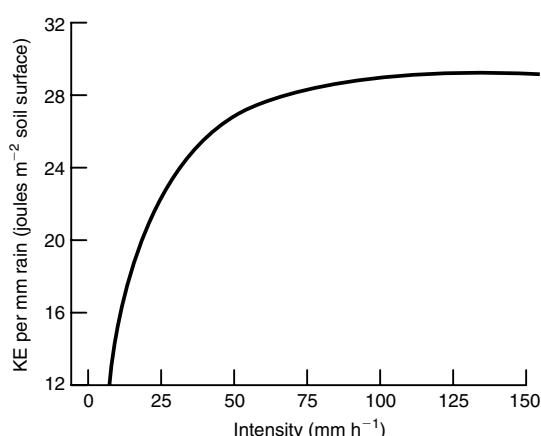


Fig. 8.1 Kinetic energy per millimetre of rain falling at different rates (mm/h). (After White, 1997.)

Later on, the palm crowns meet and provide protection from direct rainfall, but as the trunk height increases, the energy in a single large falling drop becomes larger, until it is able to disaggregate soil structure on impact (Maene and Chong, 1979). This also is concentrated under the circumference of the crown, so that local rainfall intensity is still larger. This first produces splash erosion, as above, and the disaggregated soil is readily transported by surface wash. By this age the plant cover under fully mature palms may be quite small, and serious erosion is probable if the field is on a significant slope (Chew *et al.*, 1992; Maene *et al.*, 1979). The other possible physical problem is soil compaction. Caliman *et al.* (1988) showed that compaction occurred in a West African site, and corrected it by subsoiling. This seems to be a rather unusual situation. The only situation in which compaction is frequently reported is with stock grazing between the palms (Section 8.4.3.4) or soil damage during forest clearing.

Another problem is that the chemical fertility can change for the worse. The offtake of calcium and magnesium is quite small (see Section 11.1.4), so the pH should not change markedly. In any case the oil palm is remarkably resistant to low pH values, and such a change would not be detrimental in normal circumstances. The suggestion by Caliman *et al.* (1988) that decreasing pH (to 4.67) was lessening palm growth was not proven and seems unlikely. However, from experience with acid sulfate soils it is known that the palm's tolerance limit is a little below pH 4, and it is possible that such low pHs are produced locally by heavy fertilising with ammonium sulfate. The ammonium ions are converted into nitrate ions, causing acidification, especially on light sandy soils (see Section 11.9.2.2). It must be remembered that it is not the pH (the negative logarithm of the hydrogen ion activity) that causes toxicity in soils, but the soluble aluminium that appears at the low pH values (Section 11.8.1). With time magnesium and potassium certainly decline on many soils especially if N fertiliser is applied (Tinker and Smilde, 1963a; Dubos *et al.*, 1999), and this can become yield limiting. Some soils contain large natural reserves of slowly available potassium, which become available over a period. No major detrimental change in macronutrients should occur in a well-managed and fertilised plantation.

8.1.3.7 Multiple factors

It is important to make a decision on all of these factors in combination before reaching a decision on planting. This can be done in a simple subjective way, but some systems have been developed to make the synthesis more

reliable and transparent. Paramananthan *et al.* (2000) developed the system described in Section 8.1.5. In theory, the best method for integrating all of these variables is in a mathematical model. Van Noordwijk (2001) developed a tree–soil–crop interaction model (WAN-ULCAS) to deal with oil palms and potentially with intercrops. This uses data on soil, rainfall and fertilisers to predict the yield outcome in particular situations, but its practical application has not yet been reported.

8.1.4 Previous vegetation and use

This determines the cost and time of clearing the site ready for planting, and also the amount of nutrients fed back into the soil from existing vegetation. The effort involved in clearing is roughly proportional to the mass of vegetation; thus, scrub is more difficult than lalang (*Imperata cylindrica*) and forest is more difficult than scrub (Zulnerlin and Fatah Ibrahim, 1999). The vegetation may of course provide information about the ability of the soil to support palms, but in general the effects of existing vegetation are short term and mainly affect the cost of establishment (see Section 8.3.6). There may be some carry-over of erosion hazard into the plantation phase, if there is no proper surface cover.

8.1.5 Land evaluation

8.1.5.1 Objectives of land evaluation

The objective of land evaluation here is to determine how successfully oil palm plantations can be established in a particular area (Goh *et al.*, 1994c; Paramananthan *et al.*, 2000). Many commercial and economic factors may enter into the assessment of land value, such as local transport and other infrastructure facilities, credit availability, and the quality and quantity of local labour, but the factors discussed here in detail are mostly climate, soil and water resources (Bouma, 1989). The broader modern systems have developed from earlier systems that were based exclusively on the simple parameters of soil and climate (Sys *et al.*, 1977). Site potential (see Section 10.7.2) is a more specific attempt to define the maximum obtainable yield. It is a component of a land evaluation, and is also a guide to subsequent agronomic management if the plantation is established, and how well this uses the inherent site factors of the land.

8.1.5.2 French/West African systems of land evaluation

These systems are rather specific to West Africa. The earliest was that of Olivin (1968, 1986), which has been

used extensively. The drought problems of Francophone West Africa have ensured that attention is focused on water and sunshine, with cumulative potential water deficits up to 700 mm (Nouy *et al.*, 1999). The same reasons have increased interest in irrigation (Prioux *et al.*, 1992).

The Olivin (1968) system of evaluation (Section 3.4.2.1) is based largely on potentially unfavourable soil factors. The criteria are soil texture, quantity of gravel and stones, water permeability/lack of drainage and chemical composition; of these the last has the smallest importance, because this system was designed for seasonal climates. Seven texture classes range from sand with less than 5% clay to heavy clay (over 40% clay-sized material), measured in four soil horizons (Table 3.16). There are classes of stoniness, based on the percentage of stones and gravel in the four soil layers, and four classes of drainage ranging from good to very bad (or peat). The chemical factors included are pH, organic matter and exchangeable cations. The agronomic value is judged mainly upon the stone and gravel percentage and the degree of drainage or the hydro-morphic indicators in the soil. It is interesting to compare this with the assessment of Turner and Gillbanks (1974), who paid most attention to chemical factors in their discussion of soil. This was based on conditions in South-east Asia, where drought is less important.

Olivin's (1968) classification was combined with values for the water deficit (by the IRHO method (see Section 3.4.2.1) to predict the fresh fruit bunch (FFB) yield to be expected. The soil classification is largely a means of estimating the amount of available water held at field capacity in the soil, with the maximum being 200 mm. Hartley (1988) commented that the system was reasonably reliable for the better soil classes and with a moderate water deficit. However, where there is little or no water deficit, higher yields than predicted were often found, and where there is a serious water deficit and the soils are low grade, the yields may be much less than predicted. The system therefore needs to be applied with care under less favourable circumstances.

Dufour *et al.* (1988) have produced a simplified method of production forecasting in oil palms based on climatic variables. The principle is to calculate the radiation income from sunshine hours/day in relation to the potential number of sunshine hours/day and the corresponding radiation income, and then to determine what part of this is used, depending on the water reserves at that time. These data are then correlated with yields at different times in the following period. There are similarities in principle with the concept of 'useful sunshine hours' (Hartley, 1988).

The French system should be applicable more widely to other soils in West African countries, because of the almost universal occurrence of a dry season and deep sandy clay soils, but only single-site work has been reported. Ogunkunle *et al.* (1999) studied an area in the Niger delta, and concluded on the basis of soil properties that it would be good for oil palm, but much less useful for food crops. There does not appear to be any generally accepted land evaluation system.

8.1.5.3 Indonesian systems of land evaluation

Poeloengan (1990) outlined a 'parametric' evaluation method of land evaluation, which simply means that it is based quantitatively on a series of parameters (Macrae and Burnham, 1981). This is close to a special-purpose soil classification (see Section 3.4.1.1), but it includes a few non-soil characteristics, and the prediction is based on a quantitative aggregation of the characters, rather than simply on a soil map legend. This work was based on data from the eastern part of North Sumatra, with a maximum altitude of 125 m asl and a tropical rain-forest climate. The mean temperature ranges were between 24.4 and 26.8°C and the rainfall was between 1640 and 3950 mm. Thirty-six different soil types on estates were identified, based on several different parent materials. The soils included entisols, inceptisols, ultisols and oxisols, so there were many soil types present, with a considerable range of properties.

Both composite samples and pit samples were taken, results differing only slightly between them. On these estates two standard *teneras* were planted, so the test palms were uniform. The maximum FFB yield was 30 t/ha, with the minimum yield being 10 t/ha. The land qualities that are combined in the land index are as expected; the problem is to measure them in a highly variable landscape, and from these data to decide how to define the land units, and which of these shall be designated as acceptable.

The correlations between the various variables were low, hence all were needed in the assessment. It is a little surprising that this was found for pH, exchangeable calcium and exchange capacity, which are normally closely related. The individual correlations of parameters with palm yield were also low. A multiple regression analysis showed fair correlations between yield and groups of the parameters, for example:

$$\begin{aligned} \text{Yield} = & -12.31 + 0.05 \text{ Rooting} + 3.53 \text{ Ca} \\ & + 4.49 \text{ K} + 4.11 \text{ pH} - 0.13 \text{ Water} \\ & \text{availability (yearly water deficit)} \\ & - 0.18 \text{ Erosion (slope)} \end{aligned} \quad (8.1)$$

The final calculation is of the land index (LI), as a simple multiplicative model:

$$LI = (q/p) \cdot \sum (R_i 100^{(1-q)}) \quad (8.2)$$

where q is the total number of land qualities, p is a constant, and R is the rating of the i th land quality (Poeloengan, 1990). The relative ratings of the individual site land qualities were determined from a crop requirement table. A good relationship between the LI and palm FFB yields was claimed.

Having this relationship, a land suitability classification can be made for oil palms within designated land units. The author considered that a system of this type, using standard climatic data, site and soil descriptions, should allow yield to be predicted accurately for new sites.

Adiwiganda *et al.* (1999) developed a series of 11 agroclimatic zones for Indonesia that are useful in broad evaluation studies, and that carry some similarity to the work of Olivin (1968) (see Section 3.6). They classified land mainly on climatic parameters: elevation, sunshine hours, number of average dry months and rainfall pattern (Table 3.11). Soil properties were sometimes taken into account. For example, they considered that a dry season of more than 3 months was a severe limiting factor, but it was acceptable on the best soils, such as volcanic or alluvium soils with a sandy-clay texture and good structure, that give high available water retention (see Section 3.5.1). Agroclimatic suitability classes for oil palm have been assigned from the number and the value of limiting factors for oil palm: for example 'Moderately suitable' would apply to land with more than one lightly limiting factor, or one moderately limiting factor.

Some statistical correlation systems have been developed that deal solely with the physical factors. Embrechts *et al.* (1988) developed a statistical model, based on climate, soil and site records, and fitting the yield from 36 existing plantations to these. It was claimed that yields can be predicted very accurately, but as it is a purely statistical model rather than a mechanistic model, it can only work with any degree of confidence within the limits of the area studied. Siregar *et al.* (1998) also described a statistical model in which yield could be predicted from climatic data, but this did not take soil properties into account, and so appears less general. Purba and Lubis (1990) also developed a statistical correlation system of land evaluation. They measured slope, position, and physical and chemical properties along rentices cut through forest. Each sampling point was allocated to one of four classes, having yield potentials of 20, 22, 24 or 26 t FFB/ha in the first

yield cycle. Their system of survey has been applied to 2.5 M ha between 1972 and 1988, mainly in Sumatra, and of this 1.7 M ha had been judged to be acceptable for oil palms, mainly in classes 2 and 3.

8.1.5.4 Malaysian systems of land evaluation

Kee (1995) studied the climatic rainfall pattern over Malaysia and determined places where there was a limitation to the growth of oil palms. A classification of climatic variables in terms of suitability for the oil palm was put forward by Goh (2000) (Table 3.10). However, the objective of land evaluation in physical terms is in principle close to the designation of agroecological zones (see Section 3.3.1). Nieuwolt *et al.* (1982) divided Peninsular Malaysia into ten agroecological zones. These have been regrouped according to oil palm yields by Goh *et al.* (1994c), who consider that the behaviour of yields with palm age can be defined by dividing the sites into three groups based on quantity and distribution of rainfall (Fig. 8.2) (Goh *et al.* (1994c)). The basis for the classification is essentially the liability to drought periods.

Goh *et al.* (1997) developed a broader system for evaluating the sustainability of oil palm plantations,

which used a soil map, a crop yield prediction model and an economic model. Paramanathan *et al.* (2000) expanded this to a detailed approach to land evaluation for plantation establishment, which was based on the original approach of Smyth and Dumanski (1993). They noted that the modern demand for sustainability of plantation agriculture makes it more essential than before to include the site suitability in environmental terms. They grouped the important characteristics as in Fig. 8.3, a series of 'factors', including physical, social, economic and environmental factors. These aggregate the various ratings for all land quality criteria relevant to that factor, and are themselves aggregated into a land suitability index (LSI). The physical (P) factor includes all the usual soil and climatic properties that determine the possibility of growing palms satisfactorily (Table 8.2) (Paramanathan *et al.*, 2000). The aggregation is done as follows:

$$Ps \text{ (composite score for physical factor)} = (acs \times bws \times cns, \text{ etc.})^{1/n} \quad (8.3)$$

where cs and ws are the scores for land qualities such as climate and workability, entering into the P factors, *a*, *b* and *c* are the relative weighting of each quality, and *n* is the number of qualities in the P factor.

Other factors are financial (F), environmental (E) (Table 8.3) and Social (S). The environmental properties are those essential to prevent any environmental damage, i.e. there shall only be a low probability of landslides, erosion, or soil and water pollution, given normal plantation management systems. This land evaluation system tends to reject land with slope greater than 12°, in contrast to other recommendations that envisage palm planting on up to 20° slopes. Issues such as the Conservation Act (Department of Agriculture, 1999) that aim at conservation of hill land and prevention of erosion are also taken into consideration through the environmental (E) factor (Table 8.2). The social (S) properties must indicate a realistic economic return, with acceptable risk, and benefits to the communities that live around the site.

Finally, these data are converted into an LSI by combining the factors in an analogous way to the above:

$$LSI = (w_p \times w_e \times w_s \times w_l)^{1/4} \quad (8.4)$$

where the *w* terms are the relative number of qualities assessed for each factor (Table 8.4). LSI is therefore a general assessment of the suitability of a soil mapping unit in that climate and situation. Land evaluation should be an assessment of the whole situation of a site, preferably prepared before site acquisition, but certainly before land preparation and planting. The site

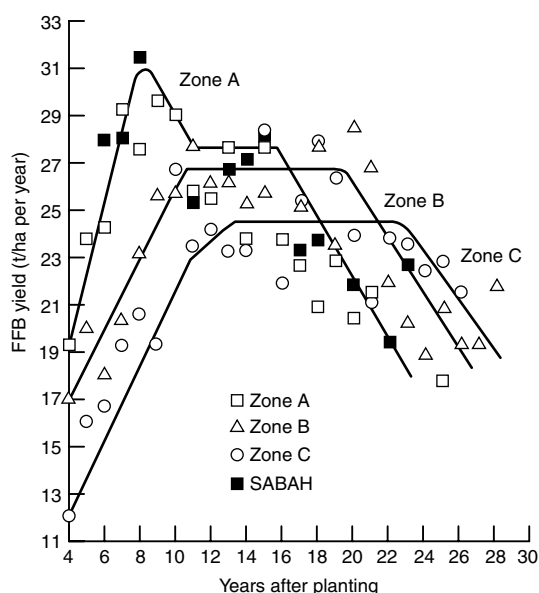


Fig. 8.2 Yield profile with time for palms growing on estates in areas of Peninsular Malaysia with different rainfall patterns. Zone A had no prolonged droughts; Zones B and C had increasing tendency to droughted periods; Sabah was similar to Zone A in rainfall pattern. (After Goh *et al.*, 1994c.)

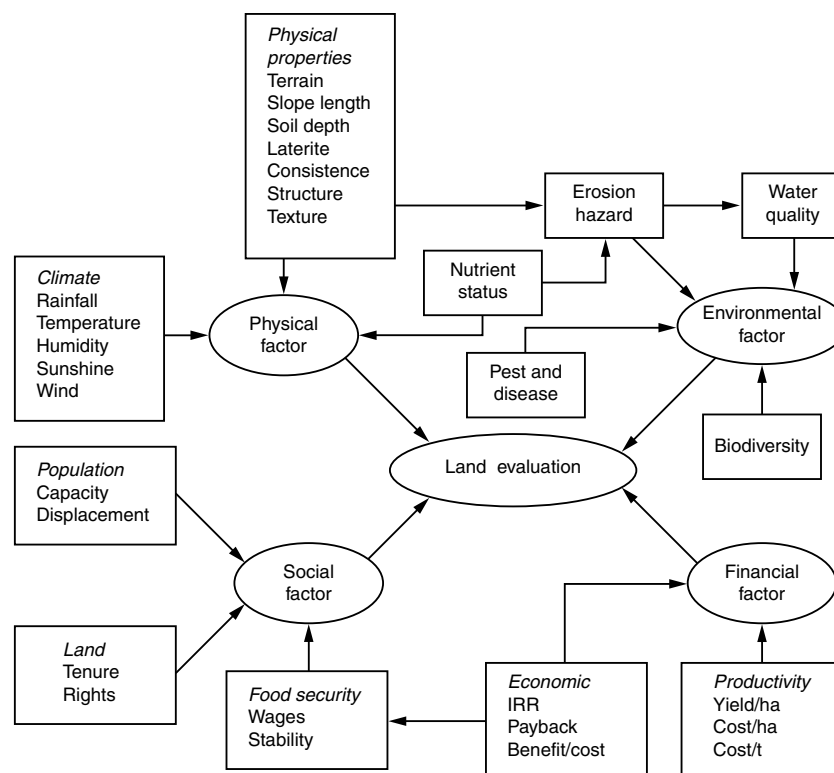


Fig. 8.3 Schematic diagram of the land evaluation process and the factors that affect the outcome. (After Paramanathan *et al.*, 2000.)

Table 8.2 Ratings for criteria entering into physical factors calculated for five mapping units with different soils

Land quality	Weightage factor	Rating for map unit (score)				
		Bdp/3	Bdp/4	Bdp/5	Mdp/1	Stp/6
Climate	0.30	S3 (0.55)	S3 (0.55)	S3 (0.55)	S3 (0.55)	S3 (0.55)
Workability	0.30	S2 (0.75)	N1 (0.35)	N2 (0.10)	S2 (0.80)	N2 (0.00)
Wetness	0.20	S1 (0.85)	S1 (0.85)	S1 (0.85)	S3 (0.65)	S1 (0.85)
Rooting	0.10	S2 (0.75)	S2 (0.75)	S2 (0.75)	S2 (0.75)	S3 (0.65)
Fertility	0.10	S2 (0.75)	S2 (0.75)	S2 (0.75)	S2 (0.75)	S2 (0.75)
Overall rating	1.0	0.13	0.11	0.08	0.12	0.00
Suitability score	5	0.65 (S2)	0.55 (S3)	0.40 (N1)	0.60 (S2)	0.00 (N2)
Potential FFB yield ^a (t/ha per year)		30–35	22–30	15–22	30–35	<15

See original paper for calculation method (Paramanathan *et al.*, 2000).

^aAssuming non-limiting agronomic and management inputs.

Suitability assessments: S1 highly; S2 suitable; S3 moderately; N1 currently not; N2 permanently not suitable.

Table 8.3 Ratings for environmental factors calculated for five mapping units with different soil types

Environmental quality	Weightage factor	Soil map unit score				
		Bdp/3	Bdp/4	Bdp/5	Mdg/1	Stp/6
Soil erosion	0.4	S2 (0.75)	S3 (0.55)	N1 (0.25)	S1 (0.85)	N2 (0.00)
Water quality	0.2	S1 (0.85)	S1 (0.85)	S1 (0.85)	S1 (0.85)	S1 (0.85)
Conservation status	0.1	S3 (0.73)	S3 (0.73)	S3 (0.73)	S3 (0.73)	S3 (0.73)
Ecological sensitivity	0.2	S2 (0.60)	S2 (0.60)	S2 (0.60)	S2 (0.60)	S2 (0.60)
Impact on ecological function	0.1	Mild (0.75)	Mild (0.75)	Mild (0.75)	Mild (0.75)	Mild (0.75)
Overall environmental factor		0.13	0.12	0.10	0.13	0.00
Environmental score/5		0.65	0.60	0.50	0.65	0.0

After Paramanathan, *et al.* (2000).

Table 8.4 Ratings for the land suitability indices for five mapping units with different soil types

Factor	Weightage factor	Soil map unit score				
		Bdp/3	Bdp/4	Bdp/5	Mdg/1	Stp/6
Physical	5	0.13	0.11	0.08	0.12	0.00
Environmental	5	0.13	0.12	0.10	0.13	0.00
Social	6	0.08	0.08	0.08	0.08	0.08
Financial	2	0.37	0.37	0.37	0.37	0.37
Land suitability index		0.62	0.59	0.52	0.61	0.00

After Paramanathan *et al.* (2000).

yield potential (see Section 10.7.2) depends on many of the components in the physical factor table (Table 8.2). The ASYP system investigates how far the yield has approached the site yield potential as derived as part of the LSI, and any reasons why this has not been attained (see Section 10.7.4).

It must be remembered that the ability to produce large yields is not the sole criterion of excellence. The high yields must also be consistent, as a mediocre and highly variable average yield cannot be properly compensated by occasional very good ones. Such a situation also places great strains on the mill and infrastructure. Data on variability of yield have been collated by Goh *et al.* (1994c) (Table 8.5). The yields with optimum fertiliser rates are generally more stable than the control yields, except for Malacca series soil. The stability of yields from Sogomana soils is notable. Stability of yield is not yet included in a final evaluation.

There is a large amount of subjective judgement involved in deciding upon the factors, constants and

criteria in most of the systems described. Despite that, this quantitative, numerical approach to land suitability is excellent because it makes soil surveyors and agronomists define their assessments clearly, and live with their assessments after the plantation has been established. However, there must remain uncertainty about the accuracy, because so much depends on the skill and experience of the person doing the assessment. This also demands a realistic appreciation of the degree to which the existing conditions can be modified, up or down, during the plantation establishment and management. In planning a plantation one must avoid a careless acceptance of risks and problems that may damage the future sustainability of the plantation, simply because of short-term commercial incentives or opportunities. The authors argue that modern methods such as remote sensing and geographic information systems can aid this process greatly. This is undoubtedly true, but it is still essential not to neglect the tedious ground observations.

Table 8.5 Variation in annual yields of FFB (t/ha) on five fertiliser experiments on important soil types in Malaysia for 7 years

Soil	Treatment	Year after treatment							Mean	SD	CV (%)
		3	4	5	6	7	8	9			
Briah	Control	33.0	40.0	27.0	20.0	21.0	23.0	22.0	25.6	5.1	20.0
	Optimum	33.0	33.0	30.5	29.0	26.0	29.0	27.0	30.6	4.4	14.2
Bernam	Control	21.5	19.5	9.5	15.0	11.0	12.0	12.0	14.4	4.2	29.3
	Optimum	27.0	24.5	17.0	23.5	17.0	19.0	24.0	21.7	3.7	17.1
Sogomana	Control	31.0	27.0	22.5	24.5	26.5	20.0	31.5	26.1	3.9	15.0
	Optimum	34.5	36.0	28.0	31.0	31.0	32.0	32.0	32.1	2.4	7.5
Rengam	Control	23.8	22.0	17.9	21.9	25.9	21.5	17.0	21.4	2.9	13.5
	Optimum	26.1	27.7	28.3	26.2	34.4	32.4	23.0	28.3	3.6	12.8
Malacca	Control	11.0	14.0	12.0	11.5	16.0	18.0	13.0	13.0	2.4	17.4
	Optimum	20.5	22.5	20.0	24.0	26.0	37.0	27.5	25.4	5.4	21.2

After Goh *et al.* (1994c).

Optimum: best treatment combination in the experiment. Control: nil fertiliser.

8.1.6 Site yield potential

This is an important concept, which attempts to determine the yield that a given site could produce if it were given perfect management treatment. The approach is valuable both in selecting sites, where it forms part of land evaluation, and in management of existing plantations. The full discussion is presented in Section 10.7.

The highest FFB yields in Malaysia are known from experience to be about 40 t/ha per year. It is not possible to give a precise value for the genetic potential of the oil palm (Chapter 4), but this highest known site potential is assumed to be close to the genetic potential. Goh *et al.* (1994c) considered that the site potential was between 31 and 39 t/ha per year in most Malaysian plantations, when the best possible treatments were given. The critical question, in relation to the choosing of new plantation sites, is thus to determine their site potential, as part of the total land evaluation. Kee *et al.* (1998) further validated this model, and showed how it can be used to help select a site for a palm plantation. There are a further two questions in this approach. First, having determined a site potential, how easy is it to obtain yields close to that potential, i.e. what level of managerial skill is required, and can that level be delivered? Secondly, how consistently will such predicted yields occur? The variability of yields between years is itself an important parameter (Table 8.5).

8.1.7 Environmental impact

The economic success of the plantation may be the first concern, but it is now essential to determine the

potential impact of the development upon the local environment. The local regulations in countries are becoming more demanding, (Gurmit *et al.*, 1999a) and the only way of showing that a plantation company takes this seriously is for it to produce formal environmental impact assessments (EIAs) for each new development. This is now a requirement in Malaysia. Ahmad Sarwani *et al.* (1999) reported on the experience of Golden Hope plantations. The pathway for the assessment is shown in Fig. 8.4, and the identified processes that may have an impact are presented in Fig. 8.5. The data collected range from geology and soil to water quality, fauna, medical and health services, etc. In this particular case soil erosion was identified as the most likely detrimental impact. As this is known before the development proceeds, plans can be made to mitigate this potential damage in good time, rather than wait for it to appear and then decide what to do. The EIA is followed up by an environmental management plan, which is then used as a guide during development. In particular, it will specify the measurements to be used to monitor environmental variables in the future so as to determine whether damage is happening (see Chapter 15).

8.2 PLANTATION LAYOUT

8.2.1 General survey and environmental issues

All procedures must be performed accurately if the plantation is to be successful. Rankine and Fairhurst

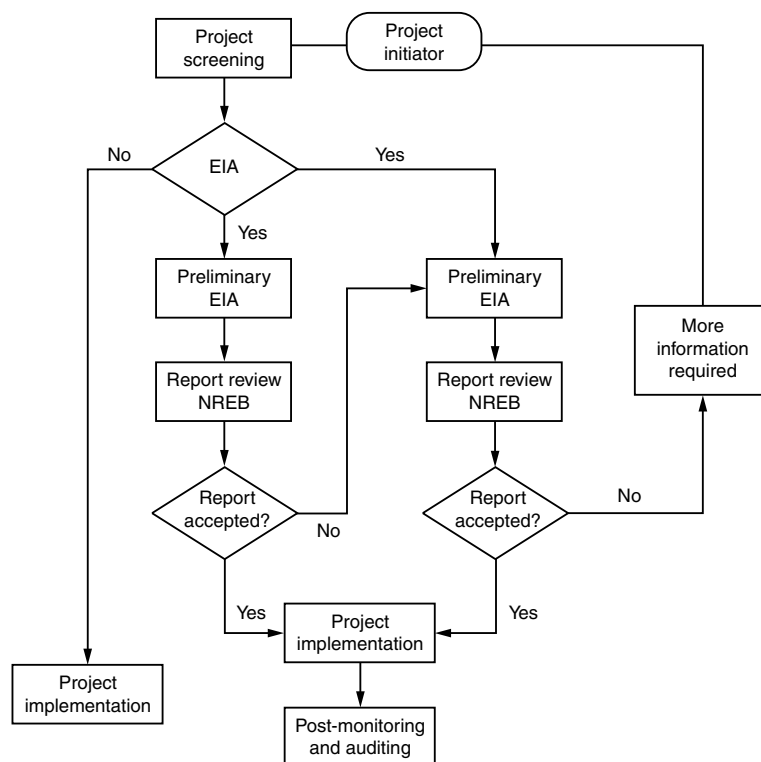


Fig. 8.4 Pathway for an environmental impact assessment of the establishment of a plantation. (After Ahmad Sarwani *et al.*, 1999.) This should be done in conjunction with the land evaluation process, as they overlap.

(1998b) gave a list of these procedures (Fig. 8.6) with estimates of the time that is spent on each stage. Some different procedures may overlap, whereas others must be carried out sequentially, and a staged plan is necessary to ensure that completion occurs on the agreed date.

The initial step is a careful survey of the area and the exact definitions of the boundaries. The land-based survey will require rentices to be cut through the standing forest, if this is the vegetative cover. This will be supported by aerial survey or satellite imagery to give precise positioning, if good-quality visual material is available. The task of surveying and laying out a plantation has been greatly simplified by GPS receivers, which can now be bought cheaply and give a remarkable accuracy in defining the point where the instrument is situated in relation to the latitude and longitude mapping grid. This means that the map of the plantation will be accurate, and can be produced in a fully digitised form by scanning, so that the terrain is defined numerically as well as graphically. This digitised map can then in principle be used in a computer-based

GIS, in which all of the spatially defined information concerning the plantation can be collected and analysed. If stereoscopic imagery is available, this allows a digital elevation model (DEM) of the area to be produced, in which the contours are plotted automatically, and may be produced as an elevation (Fig. 8.7) (Tey and Chew, 1997; Tey *et al.*, 2000). The imagery may be from satellites, where the stereoscopic quality is obtained by taking images both forwards and backwards along the line of flight, or stereoscopic air photographs may be used. This facility is particularly useful in hilly or broken terrain, where it can help to predict erosion risk. There can be difficulties if the land is covered with dense vegetation of variable height, but overall the availability of accurate maps has increased enormously since the 1980s.

There will certainly be increasing pressures to maintain greater biodiversity and wildlife in the plantation than is presently the case (Chan, 1996), and this may well require adaptations of the layout to maintain blocks or lines of forest so that wildlife can travel extensively and thus maintain large breeding populations.

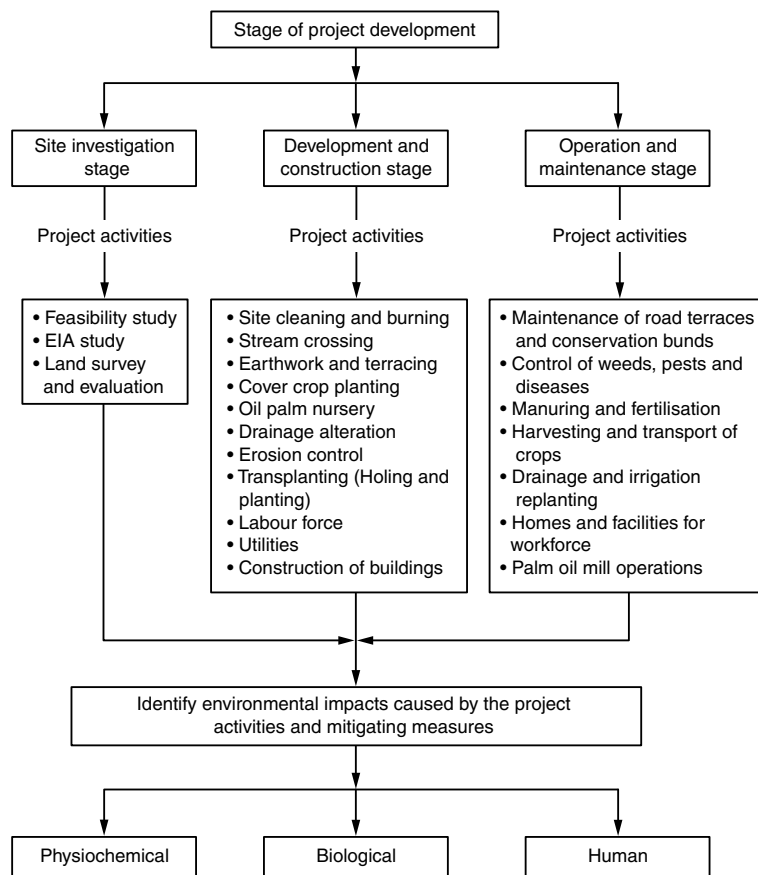
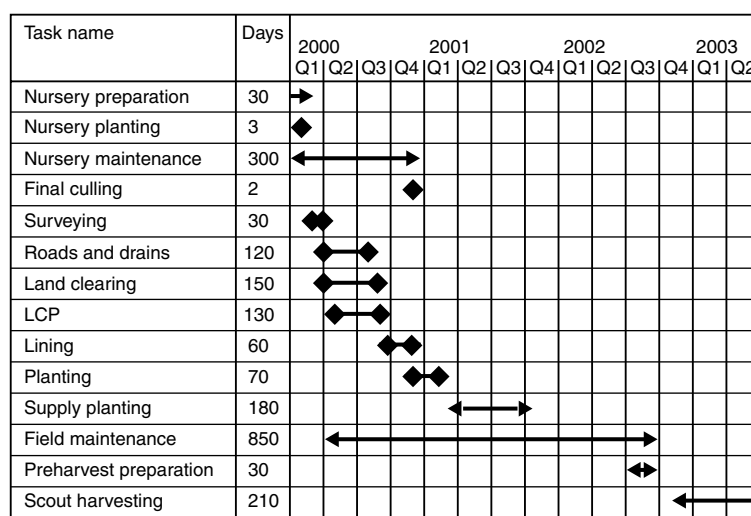


Fig. 8.5 Processes in identifying the likely environmental impacts caused by the establishment of a plantation. (After Ahmad Sarwani *et al.*, 1999.)



LCP = legume cover planting

Fig. 8.6 Schematic plan for the establishment of a plantation, with time required for each step. (After Rankine and Fairhurst, 1998b.)

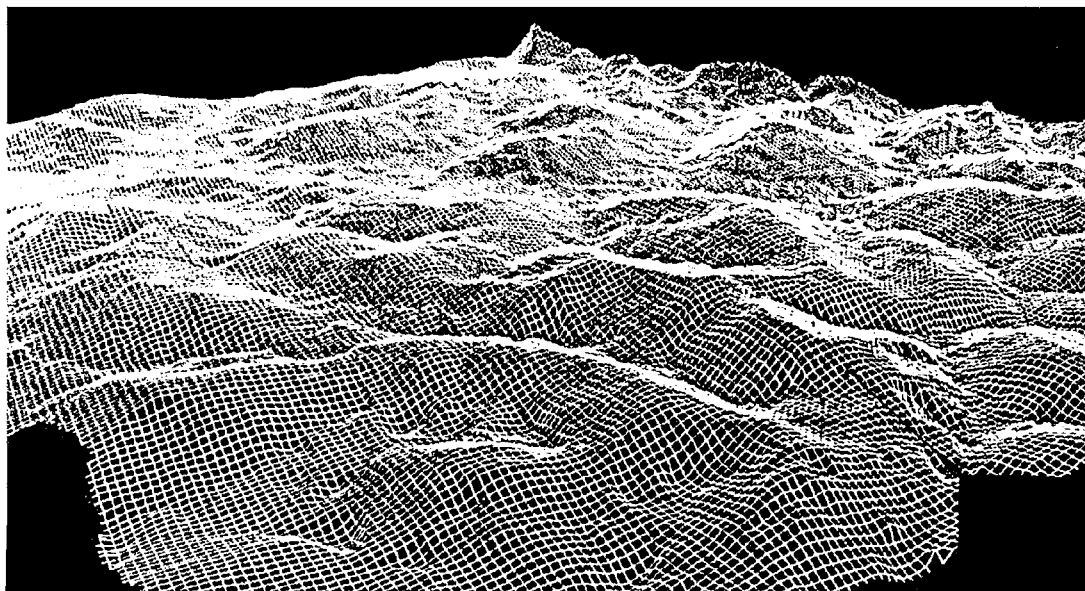


Fig. 8.7 Terrain diagram showing the three-dimensional structure of a landscape. Pixels are 2×2 m and the estate area was 560 ha. (After Tey *et al.*, 2000.)

Knowledge of the management of wildlife in a plantation is still not sufficient to meet this requirement properly (Anderson, 1996; Vis *et al.*, 2001). There are three aspects to this. First, there is a conservation aim, in that species shall not be lost because their habitat has been removed. Much more attention needs to be paid to this in the oil palm industry. Secondly, there is the belief that ecosystems (and an oil palm plantation is an ecosystem) are more stable if they have a large rather than a small biodiversity. This view is still being argued, and many cases have been found where it is not true or not proven (Lawton and Brown, 1993). Thirdly, there are questions over the nutrient, carbon and water flows in the ecosystem (Henson, 1999c). The oil palm industry probably has the necessary tools to deal with this last item, although more data are needed in some cases.

There will be continuing increases in the demands made of plantation companies in all these respects, and this requires exact planning of plantations at the layout stage; it is far more difficult to correct faults if these are embedded in the plantation layout. Both forest reserves and riparian reserves are needed, but at present there is little information about the extent and spatial layout of reserved land needed to maintain wildlife in specific areas. The terms 'landscape conservation' and 'landscape ecology' are now widely used to indicate

the scale of the planning that is needed to include plantations and wildlife habitat together in a stable system. (Andren, 1994; Hartley, 2002; Szaro and Johnson, 1996) Dufty *et al.* (2000) proposed 'analogue forests' with multiple products that are designed to support wildlife, but they are not described in a way that suggests that these would form practical plantations, as the main output appears to be medicinal herbs with unspecified markets. The basic idea may, however, be useful. Pieri *et al.* (1995) considered that forest clearance for agriculture is a major land issue, and it was taken as the first land quality indicator of state to be included alongside economic and social indicators in the World Bank Atlas (World Bank, 1995). There is much criticism of the oil palm industry on this account. Some of it is justified, but much seems poorly informed or lacking in balance. It is an issue that the plantation industry would be well advised to treat very seriously so that its case is properly presented.

8.2.2 Road systems

If possible, it is simplest to design the estate in square blocks of 25–40 ha, as this simplifies the road network. A simple design that has been used on reasonably flat land is division into 1 km^2 (100 ha) blocks, with collection

roads at 250 m intervals giving four fields of 25 ha each (Jacquemard, 1998). However, the general layout of a plantation is decided by the terrain, the drainage, the position of the mill and the length of transport of the bunches to the nearest road. A good detailed explanation of the process is given by Rankine and Fairhurst (1998b), and this is greatly aided if there is a digitised accurate map as described in Section 8.2.1. There are still some light railways working, but it is doubtful whether any new ones would be installed. Bevan *et al.* (1966) calculated that the capital cost of a railway then was over twice that of an equivalent road system, and had higher running costs. There is less damage to fruit on a railway system than in trucks, but this does not justify the higher cost (Turner and Gillbanks, 1974).

If the area is flat or gently undulating, the collection roads should be straight, and laid east–west, the palm rows being north–south. They should connect with sub-main roads running north–south, which in turn will lead to the main mill access road. If the plantation area is hilly, the roads will have to be winding, and

will have to have a greater density (km/km^2) in the hilly areas, because FFB collection is slower and more complex, even if in-field transport has been mechanised. A typical road layout for a hilly estate (Fig. 8.8) has to be arranged in relation to the drainage lines and streams. If the roads can run parallel to streams, possibly along the watersheds, this reduces the number of bridges to be built, and helps to avoid crossing swampy areas. If there are many hills, specialised systems of cable transport are available that may be economic (Hoong H.W., 2000).

The arrangement and density of roads needs to be considered very carefully because of the costs of installation, the costs of harvesting and transport, and the fact that the road area reduces the productive area of the plantation. Teo (1999) considered that a well-planned road system was even more vital if the plantation was being mechanised, in terms of road density, road gradients, road loading, road safety, and the impact upon erosion. As labour rates rise, it becomes economic to increase the road density and so to reduce the length of

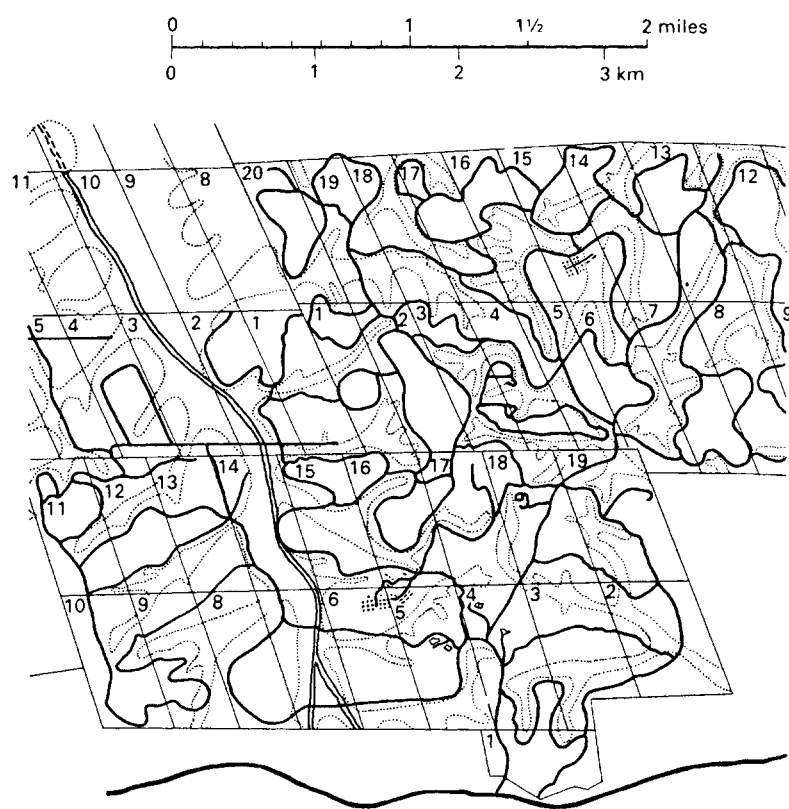


Fig. 8.8 Example of planning the road (full line) system of an estate with hilly areas. The main drainage channels (double line) and the boundaries of reasonably flat land (dotted line) are shown. (After Hartley, 1988.)

'carry' within the field. This is still true even if within-field transport has been mechanised, but proper calculations should be made of the local relative costs.

However, it is reasonable to assume that labour costs will continue to increase, so allowance should be made for this. Hartley (1988) suggested that even if 400 m appeared to be the best distance between roads at that time, 320 m should actually be used to allow for wage drift. With 320 m between roads, the density will be 33 m/ha, which will occupy some 3% of the land area. In very hilly areas the distance between roads may need to be less than 200 m because of the problems of transporting the bunches, especially with platforms or terraces. With the latter, special collection roads may be needed running between the terraces. The maximum carry distance is then rather small at 125 m, or 80 m/ha road length. Rankine and Fairhurst (1998b) considered 300 m as the normal inter-road distance, but up to 400 m maximum. Goh and Chew (2000) recommended a much higher density of 100–150 m/ha with manual collection, but 70 m/ha if in-field FFB collection has been mechanised. So there is a wide divergence of views.

Rankine and Fairhurst (1998b) also gave useful detailed practical advice on the design and building of the roads.

8.2.3 Drainage systems

As knowledge of the area builds up, the need for additional drainage channels can be identified. The drainage network needs to be planned in conjunction with the planning of the roads. On low-lying areas such as the coastal soils in Malaysia the aim is to maintain the water table not less than 50 cm below the soil surface, from where capillary rise will bring water into the main rooting zone (see Section 11.2.1). The aim is therefore to maintain water in the drains for as long as possible, and water retention systems are necessary to combat dry periods. The drains in such situations need to be wide and deep, because of the very small gradients (Plate 8.1). For acid sulfate soils, the water table should be slightly above the acid level, and the control of the water table depth is critical (Fig. 8.9). In these coastal soils the soil surface may be below the high-tide level, and the distance between drains may need to be very short



Plate 8.1 Constructing an inter-row drain with an excavator on coastal alluvium in Malaysia.

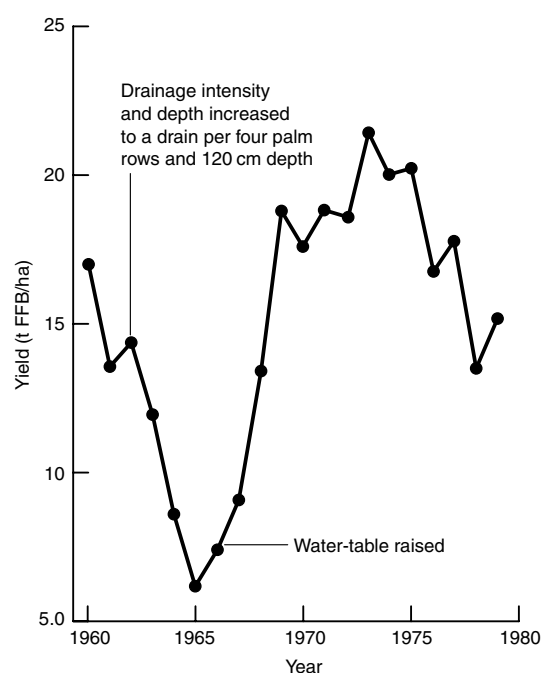


Fig. 8.9 Effects of successively lowering (first arrow) and raising (second arrow) the water table on FFB yield. On this acid sulfate soil the increased drainage decreased yield by 64%, and raising the water table increased yield to previous levels. (After Paramanathan *et al.*, 2000; originally Toh and Poon, 1982.)

(Lim *et al.*, 1994). Watergates or similar arrangements (Plate IVE) may be needed to control the rise and fall of the tides, and to prevent flooding of the soil surface, which may be due to tides or to floods in surrounding rivers (Chuah and Lim, 1989; Lim *et al.*, 1994). A layout such as the one in Fig. 8.10 is efficient in minimising the need for bridges, but maximising access, on flat land. In this type of situation it may be necessary to bund whole fields, so as to control water inflows and outflows carefully. The bund should be at least 35 cm over the highest tide, and the width of its base should be double the mean height of the tide. Hence, a 3 m tide demands a bund that is 6 m wide at the base, 3.5 m high and 1 m wide at the top. This is especially required when a layer of peat overlies the clay, as the former may dry out irreversibly if the water is drained too quickly. Good detailed guidance about the drainage system can be found in Rankine and Fairhurst (1998b), who suggest dimensions of bridges and drains, and their maintenance.

8.2.4 Irrigation systems

This will only apply in a minority of cases, but if there is any prospect of irrigation being installed, the water supply must be planned at the layout stage. The supply of water from the soil to the palm is described in Chapter 3, and irrigation aims to replace this water well before the

palms suffer from deficiency of water. Irrigation during periods of drought has been shown to increase oil palm yields (see Table 10.9). The increases are predominantly due to changes in bunch number rather than mean bunch weight, as expected from what is known of palm physiology (see Sections 4.3.3.3 and 4.4). Irrigation is discussed in detail in Section 10.3.

8.3 FIELD PREPARATION

8.3.1 General

Much less detail about these operations is given here than in earlier editions of this book (see Hartley, 1988). There are explanations with varying levels of detail in Rankine and Fairhurst (1998b, c), Turner and Gillbanks (1974), Jacquemard (1998) and Tayeb Dolmat (2000), so it seems unnecessary to repeat this here. Instead, this section will focus more upon matters of principle, especially where these are still subject to argument. It does not imply in the least that the practical aspect has been downgraded in importance. Goh and Chew (2000) pointed out that the cost of establishment in the field is at least as large as the cost of land, buildings and installations, and that it is critical that this work is well done if the plantation is to give proper returns. The effects of good versus

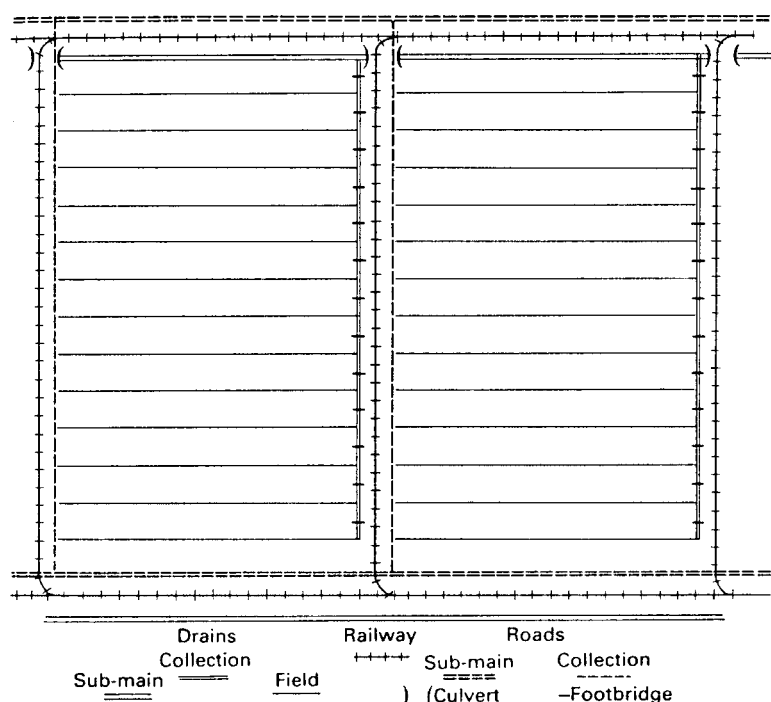


Fig. 8.10 An efficient layout of drains, rail and road systems on a flat, low-lying area. (After Hartley, 1988.)

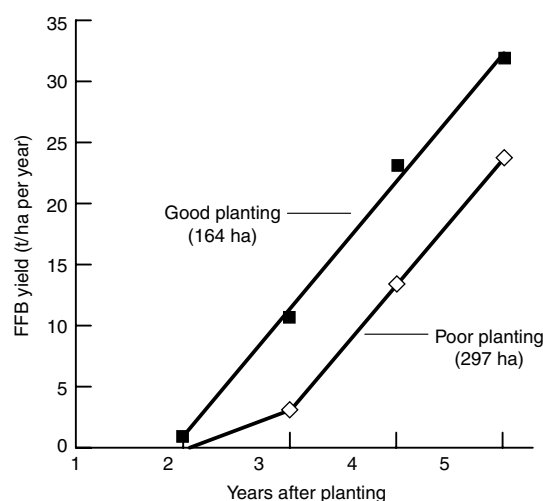


Fig. 8.11 Effects of poor planting arrangements on subsequent FFB yields; wet weather caused delayed planting, oversized seedlings and increased supplies. (Redrawn from data of Goh *et al.*, 1994c.)

poor planting work is shown in Fig. 8.11, according to which poorly conducted planting has caused a loss of yield up to at least 5 years. The loss remained fairly constant after year 3, as though the poor planting had simply delayed initial growth. The percentage difference thus decreased progressively. Caliman *et al.* (2002a) showed the close connection between the rate of growth of a seedling palm in its pre-bearing stage to the precocity of yielding and the level of the yield in the early years.

The making of a plantation involves the selection of a site, as explained in Section 8.1, and the layout of the plantation with roads and drainage. This then has to be cleared of existing vegetation. Earlier, the majority of plantations were opened from high forest, but the decrease in acceptable forested sites, and the environmental arguments against felling high forest (Casson, 2000; Gurmit, 1999; Doos, 2000), have led to the use of a wider range of sites. The environmental and legal considerations are very important now (Tayeb Dolmat, 2000). Thus, light forest regrowth, scrub and/or land covered with dominant weeds such as lalang (*Imperata cylindrica*) or Siam weed (*Chromolaena odoratum*) are now all used. The largest growth has been in the replanting of existing plantations, both oil palm and rubber, as the latter crop has slowly been displaced by the oil palm in Malaysia.

Planters will normally seek fairly flat land, but sloping land has often been used in the past, and as level land becomes more scarce, they may tend to accept

sloping land. This may require terracing or the building of platforms to prevent erosion, simplify maintenance of the palms and prevent slippage of the palms downhill. Some sites demand drainage, on flat land if the regional water table is high and the soil heavy textured (Dubos, 1988), or on sloping areas where the terrain causes water to collect and form marshes, which are often subject to seasonal flooding. In some situations drainage can be very expensive, and if so patches of flood-prone land may be left unplanted and undrained. The use of heavy machinery is becoming more common, so the concern about soil compaction should not be ignored. If serious compaction occurs a significant part of the expected gain from replanting may not be obtained. By using machinery with a relatively light loading per unit area, and by training the drivers properly it should be possible to avoid serious soil damage.

There is now also great interest in planting on peat soils (Section 8.3.6), as these are often more easily available than mineral soils, and they are always reasonably level. There are guidelines for using peat soils in Malaysia and Indonesia, but further experience is needed to ensure that these are correct and sufficient. The earliest major plantings are not sufficiently old to guarantee that peat plantations are successful in the second and third cycles.

8.3.2 Burning or zero-burning

The cost of clearing varies widely depending on the existing cover, with clearing of high forest being by far the most expensive and forming the largest expense of opening the plantation. The costs of dealing with the old palms during replanting are also considerable. Much effort has gone into minimising these costs. Measures include directional felling, to ensure that logs lie along the pathways and lines of palms to be established; greater mechanisation used in clearing, with chainsaws, winches and bulldozers; and whether to burn the felled vegetation (Plate 8.2) or allow it to rot. A major consideration here is whether the plantation is being designed for the maximum mechanisation in its productive phase. If so, it is important that cleared and levelled interlines are left through the plantation for machinery to gain access. If the forest area is to be logged over first, it is very important that this does not disturb or compact the soil excessively during the felling and extraction of the timber.

The issue of whether or not to burn the felled vegetation has remained a subject of controversy for years (Hartley, 1988). In wet areas with no marked dry season it is difficult to burn successfully, and it may become a



Plate 8.2 Before and after the burn at the end of the dry season in Nigeria.

long and delaying procedure with repeated restacking of wood and reburning. There are now rules against burning in many countries for environmental reasons (Mariana, 1999). The problem has been highlighted by the massive fires in Kalimantan and Sumatra in 1994 and 1997 and some earlier years, which produced smoke and haze over large parts of South-east Asia.

The basic arguments for and against burning (Hartley, 1988) mainly concerned the effects on the fertility in the soil and the ease of access into the field afterwards. Giardina *et al.* (2000) gave a detailed discussion of the ecosystem effects during the felling and

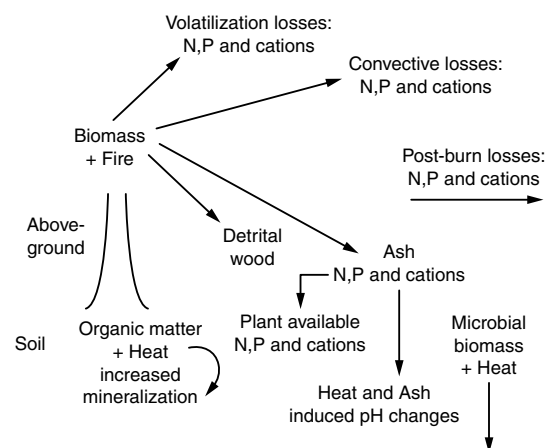


Fig. 8.12 Processes occurring during burning of residues from clearing forest: loss of ash in updraughts and in runoff, and soil changes. (After Giardina *et al.*, 2000.)

burning of vegetation (as part of shifting cultivation systems). They noted the heating effects on the soil and the consequent losses of nitrogen and sulfur, and possibly phosphorus, to the atmosphere. Figure 8.12 shows how complex the process is. On average, the remaining ash on the soil contained the following percentages of the original biomass nutrients: nitrogen 3%; phosphorus 49%; calcium 50% and potassium 57%. This suggests that there are large unknown losses, and these are almost certainly due to ash carried away in the updraught, but subsequently deposited at unknown distances from the fire (Nye and Greenland, 1960). The net loss will therefore be small on very large areas, but it could be very important on small or experimental areas.

A series of three experiments on the acid sands soils of Nigeria under widely differing rainfall (Sly and Tinker, 1962), showed that there were very few significant effects of normal burning, except for one yield effect in the early years, where palms grew best on burnt plots. Soil analyses were made at 9, 10 and 20 years after establishment, showing that the chemical differences were small and probably unimportant, both with time and between treatments (Table 8.6). Burning tended to give a larger exchangeable potassium content, and to decrease magnesium and calcium where moderate levels were present, but not where magnesium was very low. Burning caused a slight depression of organic carbon and nitrogen, as might have been expected. No leguminous covers were planted in these trials, although this might have reduced the slight loss of carbon and nitrogen.

Table 8.6 Effects of burning and not burning residues at opening up of the plantation at three sites in southern Nigeria on subsequent FFB yields and on soil analytical results

Expt	Age at soil sampling (years)	Treatment	Yield		Exchangeable cations (meq/100 g)								Exch. Cap. (meq/100 g)		C (%)		N (%)	
			First 4 years	Adult years ^a	K		Na		Mg		Ca							
			(kg ha · yr)	(kg ha · yr)	(cm) 0–15	(cm) 15–30	(cm) 0–15	(cm) 15–30	(cm) 0–15	(cm) 15–30	(cm) 0–15	(cm) 15–30	(cm) 0–15	(cm) 15–30	(cm) 0–15	(cm) 15–30	(cm) 0–15	(cm) 15–30
33–2 Benin	20	Burnt	4,860	9,947	0.045*	0.034	0.070*	0.064*	0.68	0.24	3.15	1.89	6.04	3.55	1.10	0.47	0.095	0.041
		Unburnt	5,242	9,730	0.038	0.021	0.039	0.033	0.63	0.27	3.82	1.89	6.27	3.43	1.20	0.49	0.100	0.041
3–4 Benin	10	Burnt	4,958*	6,549	0.070	0.047	0.048	0.038	0.69	0.43	2.18	1.07	5.87	4.93	1.18	0.73	0.098	0.061
		Unburnt	4,363	6,499	0.073	0.045	0.056	0.041	0.83*	0.47	2.75*	1.39	6.15	4.70	1.24*	0.68	0.106*	0.059
506–2 Abak	9	Burnt	2,617	6,038	0.073	0.049	0.044	0.042	0.15	0.08	0.14	0.10	6.01	5.16	1.14	0.79	–	–
		Unburnt	3,017	6,168	0.073	0.040	0.046	0.028	0.16	0.09	0.13	0.07	6.01	5.10	1.19	0.76	–	–

After Hartley (1998).

^a Means of 11 years (33–2), 6 years (3–4) and 7 years (506–2). (Field numbers)

* Significant difference at $p = 0.05$.

Other work has had variable results, but overall there seems no good evidence that well-conducted clearing and burning has any significant negative impact on the future success of the plantation, unless the soil is already extremely depleted (Hartley, 1988). The state of the soil is probably more influenced by how it is treated subsequently to clearing and burning. Poor use of heavy machinery can have serious long-term effects on some soil types. In South-east Asia burning of felled palms during replanting has been recommended on the basis that it diminishes the attacks of *Oryctes* beetles on the new seedlings, after their breeding in the felled palms. However, burning may be a slow and cumbersome procedure, and the argument for and against has swung in both directions. In any case, the environmental arguments

mentioned above are now dominant, and burning has been outlawed in Malaysia. Most recent research has therefore focused on zero-burn procedures, as follows.

Khalid *et al.* (1996b, 1998, 1999a–c) compared replanting after felling the old palms with an excavator with a chipping bucket. The following treatments were applied: removal of the felled stand from the field; chipping and shredding the old palms; chipping and pulverising the palms; or partially burning the chipped palms to the extent allowed by the weather. The initial amount of dry matter was 85 t/ha in the trunks, and 16 t/ha in the roots, so there was a considerable amount of material to deal with. Growth parameters of the replants were monitored over 24, 36 and 48 months (Table 8.7). The best results were obtained with chipped

Table 8.7 (a) Vegetative growth of palms with four different treatments of residues after replanting

Treatment	Months after treatment	Frond length (cm)	Frond dry wt (kg)	Leaf area (m ²)	Trunk diameter (cm)
Complete removal (C/R)	24	199	0.91	2.06	29.8
	36	269	1.09	3.26	49.8
	48	372	5.21	4.57	56.5
Chipped/shredded (C/S)	24	237	1.10	2.42	41.0
	36	313	1.19	3.69	53.7
	48	403	5.75	5.03	62.3
Partial burning (P/B)	24	219	1.01	2.27	36.1
	36	300	1.21	3.59	53.9
	48	399	5.66	5.05	58.5
Chipped/pulverised (C/P)	24	228	1.04	2.38	38.3
	36	291	1.09	3.39	53.2
	48	380	5.23	4.44	59.5
LSD (0.05)*	24	13.7	0.05	0.16	3.7
	36	20.0	0.13 (ns)	0.46 (ns)	2.2
	48	27.0	0.41	0.55	3.1

(b) Yield of FFB with four different treatments of the residues after replanting (as in part a)

Treatment	Months after treatment	FFB yield (t/ha per year)	Bunch wt (kg)	Bunch no./palm per year
Complete removal (C/R)	25–36	4.6	3.6	9.1
	37–48	11.1	5.1	16.7
Chipped/shredded (C/S)	25–36	10.5	4.0	18.8
	37–48	15.2	6.5	17.2
Partial burning (P/B)	25–36	7.2	3.8	13.6
	37–48	12.1	4.7	18.9
Chipped/pulverised (C/P)	25–36	7.2	3.0	17.2
	37–48	11.8	6.0	14.3
LSD (0.05)*	25–36	2.31	0.54	3.94
	37–48	1.92	1.23	4.75 (ns)

After Khalid *et al.* (1999b).

Figures are means of four replications.

*Significant at $p = 0.05$; ns: not significant.

and shredded trunks, the worst with complete removal, where the exchangeable potassium in the soil was much diminished, as is to be expected. The procedure that included burning was intermediate.

The hypothesis in this work was that the release of nutrients from the old stand must be synchronised with the demand from the young palms, which is indeed very desirable (11.7.1). This is discussed in detail in Chapter 11 in relation to the long-term nutrient cycling on fields carrying sequential crops of oil palms. Field palms given the normal fertiliser treatment grew better, and had higher nutrient contents in the leaflets, than any of these treatments, suggesting that none of them achieved adequate recycling.

Zulnerlin and Fatah Ibrahim (1999) have given a good discussion of the practical zero-burn procedures used in Sumatra, in planting on forest, areas covered with scrub or lalang (*Imperata cylindrica*) and replanting on oil palm land. It was essential to line-out in the field before felling, to guide the placing of residues from clearing. They compared windrowing, in which trunks and residues were piled in lines by machinery and allowed to rot down, with prior shredding using an excavator with chipping bucket attachment. They favoured windrowing without shredding, to avoid the use of so much heavy machinery that compacted the soil. In both cases the residues were piled in every third interrow between planting sites, so leaving two out of three interrows completely clear. These were then both ploughed and harrowed, and sown with cover crop seed, to produce a level surface for machinery to pass. This last treatment also helped establishment of cover plants, increased the decomposition rate of the residues and lessened *Ganoderma* attack. The *Oryctes* population at the last measurement was zero with a good cover crop and with burnt shredded residues, 0–19 per 100 m² in treatments where the residues were not burnt, and 648–740 per 100 m² in the factory dump. The main advantage of this procedure are that it is environmentally friendly, can proceed right round the year and improves the soil. The main problems were found to be pests: termites (Sudharto *et al.*, 1993), rats (Section 12.3.1) and *Oryctes* (Section 12.2.4.1). The termite *Coptotermes curvignathus* (Table 12.11) has two subspecies, of which one tends to feed only on dead tissues, while the other bores into living tissue and can kill a young palm. *Macrotermes gilvus* attacks the root systems.

Hashim *et al.* (1995) discussed experience in Malaysia and Indonesia on the basis of the zero-burn system used commercially, and concluded that in general zero-burning was satisfactory. Abdul Majid (1999) and Loh and Sharma (1999a) agreed with this view. The latter emphasised that

during replanting the opportunity must be taken to improve layout and other factors that have been found to be inefficient. They recommended a zero-burn procedure, with control of *Oryctes* by reducing the biomass of old palms left on site, which also favours later mechanisation. Good field supervision was regarded as vital. With these high inputs they expected yields of >30 t FFB/ha to be achieved with 5–9 year-old palms.

Goh and Chew (2000) have also discussed these procedures in detail, dealing with replanting from oil palm, rubber and cocoa. The last two are even simpler than replanting from oil palms, since rubberwood can be sold off, and cocoa trees are easily cut up and removed. It seems reasonable to assume that zero-burning will be the standard method in future, although it will need more careful attention to pests that attack the seedling palms. It seems that a degree of consensus has been achieved, at least in South-east Asia, for zero-burning during replanting, with chipping and breaking up debris, following on from the poisoning of the palms. Burning is now recommended rarely, and is forbidden in Malaysia and Indonesia. However, Rankine and Fairhurst (1998b) gave detailed advice on burning, and it seems likely that it will continue in some countries, so it is considered here.

8.3.3 Operations in land clearing

8.3.3.1 General

The sequence of land preparation and planting operations has shifted in various ways over the years, in ways that may seem trivial, but that can make large differences in cost. They may also affect yields for several years (Fig. 8.11), and it is not certain that the yields of well and poorly planted palms will ever become equal. The favoured procedure has gone from non-burning (on grounds of soil fertility), to burning (on grounds of convenience and phytosanitation) and back to non-burning (largely on environmental grounds). The largest change has probably been the introduction of mechanical methods. In the earliest edition of this book it was assumed that land preparation is done by manual labour; in the third edition (Hartley, 1988) both methods were mentioned. Hartley stated that, in 1985, fully mechanised methods could only be justified on grounds of profitability if there was a shortage of labour. In fact, this shortage has occurred in Malaysia, with the accompanying increase in wage rates, and the advantage is shifting towards the mechanised methods, as has happened in all other agricultural systems. At present, mechanical methods are likely to be used in all major oil palm-growing countries, and we have assumed

this here, although even the best machinery will always need a significant amount of ancillary manual labour.

Details of practical procedures to be used in the field are given by Rankine and Fairhurst (1998b), covering areas initially carrying high forest (jungle), grassland or tree crops. They advised against windrowing of tree trunks, following the removal of useful timber and the cutting up of trunks to manageable lengths, to avoid compaction of the soil, but this seems difficult if open avenues are to be left for machine access and there is a zero-burn policy. However, in this manual full directions are given for burning of felled trees as one option. The actual directional felling is done by chainsaws and axes, but these authors advise against the use of bulldozers for removing stumps, again on the ground that the soil is disturbed and compacted. This differs from much current practice. Chikwe (1995) tested a variety of equipment in Nigeria, and found that the cost of manual and mechanical methods was approximately equal for secondary forest, but the manual method was most efficient in primary forest. This was similar to the findings of Turner and Gillbanks (1974), possibly because Chikwe was working in a situation with ample labour available, similar to the situation in Malaysia before 1974. This increased employment of labour in manual methods of clearing was regarded as a social advantage because it reduced unemployment. The only disadvantage of the

manual methods was the large amount of heavy timber and large stumps left that obstructed the avenues; but on the other hand mechanised methods of removal were found to cause serious soil compaction.

8.3.3.2 Planting from forest

Some of the systems discussed by Hartley (1988) are reproduced here to indicate the changes with time, particularly the increasing use of machinery. After roads, block boundaries and drainage channels have been established, the following procedures are carried out.

- *Congo* (1952): Underbrushing; felling trees; heaping; burning; lining out; clearing paths and planting lines; terracing; sowing cover crop.
- *Ivory Coast* (1961): Underbrushing; first lining; directional felling; stumping and cutting up; light burn; second lining; heaping wood in windrows; levelling and clearing planting lines; sowing cover crop. Heavy tractors had no difficulty dealing with small and medium trees, but buttressed trees over 75 cm diameter had to be dealt with in stages, and there were normally a few trees per hectare that had to be felled manually. Trunks were cut up with chainsaws, first lining out was done, and the cut-up trunks and branches were windrowed as in Fig. 8.13

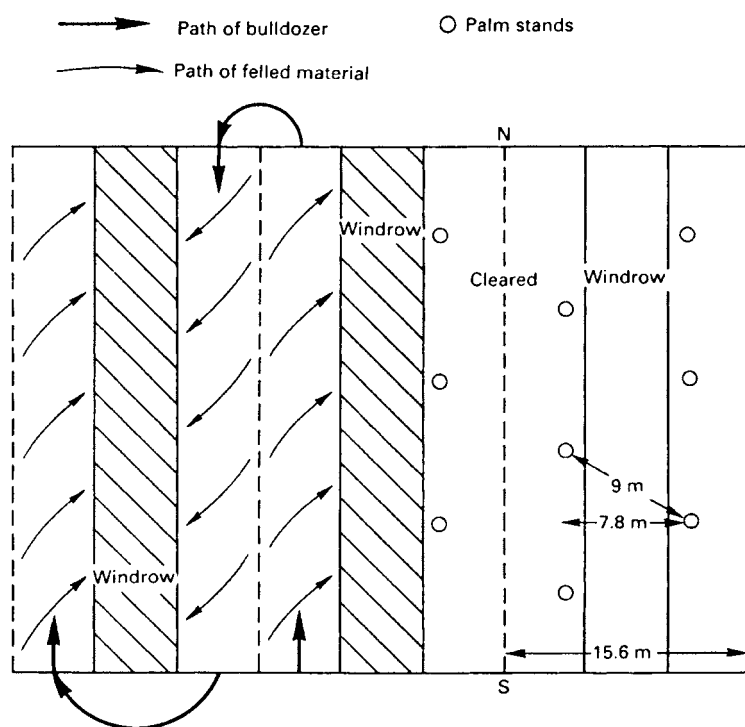


Fig. 8.13 Organisation of clearing of debris by bulldozers, after forest felling in the Ivory Coast. (After Hartley, 1988; Huguenot, 1963.)

(Hartley, 1988), the time taken being three tractor-hours/ha, depending on the density of the forest. It took some time for the trunks to rot down, and maintenance of the windrow avenues was difficult until this happened.

- *Nigeria* (Sly *et al.*, 1963): Underbrushing; lining; holing; felling with chainsaws and axes; burning; cutting trees into 6 m or less lengths; moving trunks into the planting line, between planting holes, with tractor; reburning the timber (Plate 8.2). This simpler method used lighter tractors and avoided the extensive soil disturbance caused by the above methods. All avenues were available for trailers carrying seedlings, and for mechanical maintenance, but not burning the amount of unburnt timber left along the palm rows in this method might cause problems.
- *Malaysia* (1969): Underbrushing; felling; burning; cutting and stacking; reburning; clearing planting paths; sowing cover crop. Khamaruddin (1980) tested manual plus chainsaw felling and stacking, against the same for felling, but using tractors for stacking the timber; and using bulldozers for both felling and stacking. At the time this last was by far the most expensive. The costs of the other two were comparable, but the second was the most convenient.
- *Indonesia* (1999) (Zulnerlin and Fattah Ibrahim, 1999): Underbrushing; directional felling; lining out; stacking of debris in windrows with two clear interrows out of every three; final lining out; sowing cover crop. This method has been discussed above.
- Rankine and Fairhurst (1998b) do not state a specific sequence of operations and the implication is that this can be decided on the basis of local conditions, but their book is laid out in the following order: underbrushing; directional felling; (burning); lining out and clearing planting avenues; sowing cover crop. Where the land is steep, the sequence is as above, but terraces are first constructed by bulldozer, and felled woody debris is pushed outwards together with the soil. On peat, burning must not be used, and drainage must be done before any other step. After the peat has partially dried out the sequence is: fell trees; stack dried timber and compact peat in cleared double line. Planting is by the hole-within-hole technique (see Section 9.1.2).

8.3.3.3 Planting from other vegetation

Where high forest has been felled earlier, and the land has been cropped for food and possibly later abandoned, it does not necessarily revert to forest. If the soil has been exhausted it may remain under grass, especially if this is burned at frequent intervals. In

West Africa this produces 'derived savannah' in low-rainfall areas, and this process may be encouraged by heavy grazing. Sometimes there is strong growth of *Chromolaena* or lalang, which burn easily in dry weather, and so prevent the re-establishment of trees.

There is no reason why land that has become overgrown with weeds and grass, possibly after exhaustive food cropping, should not be converted to satisfactory oil palm plantations, but if much soil fertility has been lost it may require special treatment with fertilisers (Hartley, 1988). In grassland the main operation is to remove obstructions, slash the grass, and kill it in the planting lines with herbicides. Mechanical cultivation is then used to prepare seed beds for leguminous cover plants, and planting can proceed. The cost of opening up is much lower than for forest. Lalang can be eradicated by disc ploughing and harrowing (Hartley, 1988) followed by a straight-tine cultivator, but modern herbicides such as glyphosate (Roundup) are cheaper and more effective. Normally, small patches of lalang persist, and have to be removed manually. Such cultivation treatments produce a good seedbed for cover establishment (Rankine and Fairhurst, 1998b), and the early establishment of legumes is important. Zulnerlin and Fattah Ibrahim (1999) recommended that where the original vegetation was lalang, the procedure should be: line out; slash grass in palm row; repeated (glyphosate) herbicide spray; sow cover crop; slash interrows; spray paths with herbicide. Where the original vegetation was scrub, procedures are similar to those with grass, but bushes and shrubs have to be cut and piled in the interlines. Where there is no dominant weed it may be possible to plant out directly, after clearing the planting sites and digging the holes, but such areas may have very infertile soil.

In South America large areas of grassland have been converted to oil palm. These grasses (*Hyparrhenia rufa*, *Panicum maximum* or *Pennisetum purpureum*) are large and vigorous, and totally different from the poor and stunted grassland discussed above; the soil will also carry a large seed burden. The eradication of these grasses with herbicide, and their replacement with a vigorous stand of legumes, is essential (Hartley, 1988). *Brachiaria* has been planted as a pasture grass in a number of areas, and this grass is similarly vigorous. One way of eliminating this grass on level ground is to take one or two crops of paddy rice before planting oil palms.

8.3.4 Replanting from oil palms

8.3.4.1 The decision to replant

This is now a very important issue, because Malaysian replanting is thought to have been relatively neglected

(see Sections 1.4.3.2 and 10.6.2). Large areas of old plantation have already reached the point where they should be replaced because the palms are too tall for efficient harvesting. If new planting material is to be introduced at a reasonable rate, the speed of replanting may have to be increased from that of recent years in Malaysia, which has the largest amount of old plantation land. Basiron (2000) suggested that some 5% of the Malaysian oil palm area (*c.* 150,000 ha) should be replanted each year, both to upgrade the quality of the plantations and to help to support the price of palm oil. In fact, 5% of the area per year will give a 20-year planting interval in a steady state, which is certainly smaller than the current mean replanting age. However, the most recent information (Khoo, 2001) (Table 10.18) shows that the age profile is not so very serious at present, despite the many recent calls for more rapid replanting. Only 21% of the palms are over the age of 19, and 43% are below 8 years. However, 7% of palms are well over 25 years old, and these need replacement urgently.

Where a plantation is started on new land, it will be fully planted up as soon as possible, say over a period of 4 years. To avoid the problems of replanting over such a short time, replanting may be started early and finished late, in order to smooth the age profile. The aim is to replant regularly at 4–5% per year when in a steady state.

This is an important issue for the industry as a whole. Plantations have a difficult judgement to make in deciding at what age to replant. Figure 8.2 shows clearly that high yields tend to decline markedly with age, but that there is considerable variation in this effect. In the first 2–3 years the young palm is only contributing a small yield, and the whole replanting procedure causes a loss of FFB as a cash cost. A careful calculation with discounted cash flow is needed to determine the best policy. One argument advanced for replanting early is that new material will yield more heavily. However, there is little evidence for the rising yield profile that would be expected on this argument (Tinker, 2000a; Jalani *et al.*, 2001). The argument about the relation of oil extraction ratio (OER) decline to palm age is also relevant (see Section 10.5.3). All of these issues are debatable and need more research, but the determination of the best replanting age for each plantation is a very important question to be settled within the Malaysian oil palm industry at the present time.

The economics of replanting suggest that two points should be considered. Firstly, it is necessary to keep the old palms bearing as long as possible, to avoid the gap in the earnings stream during the replanting and early years of the new palms. This argues against reducing the fertiliser treatments in the last years, unless it is

certain that there is no loss of yield. The discussion below suggests that this means that manuring should be stopped only in the last year before the replanting, even if such stoppages could increase the overall fertiliser efficiency by decreasing the internal concentration of nutrients in the palms before they were felled.

The second point is that the amount of nutrient in the old stand is large compared with what the new stand can take up rapidly. Underplanting means that the nutrient input from the old stand is distributed over, say, 2 years, and therefore has a better chance of being absorbed by the new palms. No research on this appears to have been done. The chips from the old trunks could be distributed around the new palms (so long as this does not encourage pests) so as to bring the nutrients closer to the new rooting systems. By the third year the new palms are much larger and contain a significant amount of nutrients. The best way of organising replanting to conserve nutrients needs to be determined, as the loss on replanting is presently the largest cause of loss during a planting cycle (see Section 11.7.1).

8.3.4.2 General procedure

In principle, the procedure for replanting is the same as planting from forest. If the palm spacing remains the same, the lining out has effectively been done, but sometimes the plantation layout may need complete reconsideration. In particular, this is the moment to consider future mechanisation policy and the need for any infrastructure changes such as increased road density.

Replanting may start by poisoning the old palms. Various methods using poisoning of the old stand have been tested, but it is usual to poison the palms by injection with a herbicide such as paraquat or glyphosate (Rankine and Fairhurst, 1998c). Any poisoning method may cause problems with the dying crowns, and poisoning now seems a less popular procedure. At present, the most popular technique for felling palms at replanting is to push them over with a digger or bulldozer (Goh and Chew, 2000), uproot them with a bulldozer into the direction of the new planting line, and windrow the trunks and fronds together in the new interline space. This gets rid of the bole at the same time. This is more complex if the planting density or layout is to be changed, when the field or block has to be relined. This task should be done first as it simplifies the disposal of the felled palm material.

It used to be recommended that old palms must be killed and removed, to prevent *Ganoderma* outbreaks after planting. It is now much more common to shred the trunks and boles of the felled palms with a chipper

blade mounted on an excavator, and spread them in chosen interrow avenues. The cover crop is sown on top of this, and the debris is left to rot down. The major problem is of pest attack, by rhinoceros beetle, termite and rodents, in the early years, and by *Ganoderma* in later years. If it is environmentally acceptable and legal, some planters still favour burning the palm debris to improve phytosanitation.

A more elaborate method for land that is flat, low-lying and difficult to drain was reported by Santa Maria *et al.* (1996), who called it the 'cambering-pulverising' system. This involved felling *Ganoderma*-infected plants and disposing of these first by chipping and burying them. Next, windrows were marked out, one for each four palm rows. The soil was scraped away to leave a dip, the soil being reserved, and a drain was dug along the centre of each one. The remaining palms were felled, chipped and stacked along the windrows, root bole tissues being placed on top. The reserved soil was then piled up to form a camber (Santa Maria *et al.*, 1996) (Fig. 8.14), approximately 30 cm higher than the drains, which were rolled to compact them. Finally, after planting the seedlings, chips were used to mulch them, and remaining tissues were pulverised by machine, to destroy rhinoceros beetle breeding sites. This procedure is expensive, and successive pulverising treatments of the chips are needed subsequently, but the expenditure was considered to be justified by the good results.

Very recently, another approach to this problem was made by Ooi *et al.* (2001). The essential part of this was to chip the trunk into pieces considerably smaller than normal (2.9×0.2 cm) with a special machine (the EnviroMulcher) and to spread these evenly throughout the plantation. The residual material, the palm crown, fronds and the palm boles, were buried in trenches dug in every fourth or every alternate interrow. This system reduced the breeding of *Oryctes* to about 2% of that with the normal chipping system under similar conditions. The trunk chippings could be used to mulch the young palms, and were found to contain enough nutrients to support the new stand of palms for over 3 years (see Section 11.7.1). The rate at which the nutrients became available was not measured. It is clear that a system that simultaneously prevents the breeding of

Oryctes, transfers nutrients at a desirable rate from the old stand to the new, and leaves the field in a state that is convenient for future mechanised work, is being sought in various ways. Further work is needed to determine the lowest cost of achieving these objectives, but considerable progress has been made, and final success will undoubtedly be achieved. Yow and Jamaluddin Nasir (2001) have detailed the strategies and policies used in one of the larger Malaysian plantation companies, Golden Hope.

Nazeeb *et al.* (1995) investigated the possibilities of ceasing to fertilise the old stand for a period before felling began on a field on inland soil due for replanting. The FFB yield started to decline below that of fertilised palms in the year following cessation (Table 8.8), the decline being consistent over three soil types and several years. Knowing the large nutrient reserves in well-fertilised old palms (see Section 11.1.4), it is quite surprising that yields without fertiliser fell below fertilised yields so soon. However, Teoh and Chew (1988a) found that well-manured palms on Malaysian coastal soils would continue to yield without potassium fertiliser for at least 6 years, but on inland soils only 2 years. The conclusion of Nazeeb *et al.* (1995) was that a saving was possible by not fertilising for a very few years before felling, but this would depend on the relative prices of fertiliser and palm products, and the possible savings beyond 1 or 2 years were unlikely to be important. Teo *et al.* (2000) studied the effect of not fertilising in a large and detailed experiment. Their conclusion was that no more than 1 year without fertiliser was advisable, as there was a progressively greater decrease in yield with 2 or more years without fertiliser. In general fertiliser should be supplied so long as the additional FFB covers the cost of the applied fertiliser.

Replanting in Sabah is still fairly small, because of the more recent opening up of plantations there, but it was investigated by Ho and Chiang (1999). They recommended zero-burning and clean clearing, the latter to simplify mechanisation, with shredding of palm trunks. As a precaution against *Ganoderma* attack they recommended that palm boles are excavated and chipped, and the holes filled with soil. They suggested that fields will often need to be realigned because the infrastructure

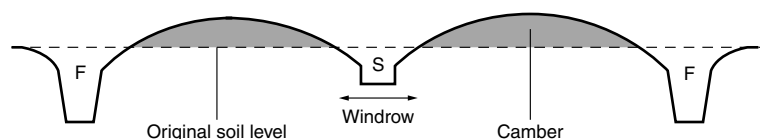


Fig. 8.14 Arrangement of ridges and drains in 'cambering' system of planting on wet land. F: field drain; S: scupper drain. (After Santa Maria *et al.*, 1996.)

Table 8.8 Effects of ceasing to manure palms on Rengam soil that were due to be felled later, on their FFB yield bunch number and bunch weight over different periods

	FFB (t/ha per year) Year after cessation of manuring						
Treatment	1st	2nd	3rd	4th	5th	6th	Total
Manuring ceased	20.67	23.72	23.83	28.31	19.76	18.10	134.39
Manuring ongoing	23.07	28.51	26.89	34.69	25.12	27.27	165.55
SE of mean	1.56	1.31	1.20	1.22	0.87	1.12	5.62
Var. ratio	ns	*	ns	*	**	**	*
	Bunch no. per ha per year Year after cessation of manuring						
Treatment	1st	2nd	3rd	4th	5th	6th	Total
Manuring ceased	812.5	875.7	818.6	958.9	736.9	772.6	4,975.2
Manuring ongoing	901.9	1,036.0	877.2	1,117.7	866.4	948.1	5,747.3
SE of mean	46.8	42.5	40.1	42.6	23.2	45.5	184.9
Var. ratio	ns	*	ns	*	*	*	*
	Average bunch weight (kg) Year after cessation of manuring						
Treatment	1st	2nd	3rd	4th	5th	6th	Total
Manuring ceased	25.44	27.08	29.03	29.55	26.74	23.29	26.95
Manuring ongoing	25.61	27.58	30.72	31.13	28.99	28.79	28.83
SE of mean	0.97	0.37	0.42	0.40	0.88	1.13	0.58
Var. ratio	ns	ns	*	*	ns	*	ns

After Nazeeb *et al.* (1995).

** $p < 0.01$, * $p < 0.05$; ns: not significant.

must be improved to cope with mechanisation and with higher yields. Basically, this is similar to elsewhere in Malaysia.

8.3.4.3 Underplanting the old stand

A major cost of replanting is the loss of income in the years when the field carries no bearing palms. There is consequently much interest in underplanting, i.e. keeping some of the old stand so that it can continue to yield after the new stand is planted and removing it when the new palms are in bearing. The old palms are removed over a period by being felled with a bulldozer,

or poisoned with a herbicide and allowed to rot without being felled. However, the new palms develop more slowly because of initial shading, and there is a concern over increased risk of *Ganoderma* and *Oryctes* attack, so there is argument about whether the more complicated procedure is worthwhile in terms of a larger total FFB yield.

As noted in Section 8.3.4.1, if replanting is started early, underplanting may be considered. Some of the earliest work on underplanting was done in the Congo by Ferwerda (1955). He observed: 'The ideal replanting procedure would be a system whereby the annual production from the replanted area never falls below that

Table 8.9 (a) Yields in Yaligimba replanting/underplanting trial

Treatment Proportion cleared in				Yield (t FFB/ha)					Total
				Old stand	Young palms				
1953	1954	1955	1956	1953–56	1956–59	1959–60	1960–61	1956–61	1953–61
All	–	–	–	0	23.2	11.9	8.9	44.0	44.0
2/3	1/3	–	–	2.8	19.4	10.8	9.3	39.5	42.3
1/3	1/3	1/3	–	9.7	18.3	11.1	10.1	39.5	49.2
–	1/3	1/3	1/3	17.1	12.7	9.6	9.6	31.9	49.0

From Unilever (1961).

All replanting of young palms was done in 1953: the fractions of the old stand felled in each year are shown, with total yield from the old stand 1953–1956 and yields from the young replants over the periods shown.

(b) Yields from replanting/underplanting in Malaysia

Treatment Proportion cleared at					Yield (t FFB/ha)							Old + young
					Old stand	Young palms (year of production)					Total	
0 m	3 m	6 m	12 m	24 m		1	2	3	4	5	Total	
All	–	–	–	–	0	1.6	10.6	17.4	20.0	13.4	63.0	63.0
–	All	–	–	–	8.7	0.7	7.7	13.9	19.1	12.2	53.6	62.3
–	–	All	–	–	11.9	0.2	6.5	11.9	21.3	10.1	50.0	61.9
–	–	–	All	–	22.0	0.0	6.1	8.9	19.2	11.6	45.8	67.8
50%	–	50%	–	–	8.4	0.5	8.7	15.8	21.6	12.3	58.9	67.3
–	–	50%	50%	–	15.9	0.3	7.5	11.7	19.8	12.2	51.5	67.4
–	–	50%	–	50%	27.4	0.1	6.5	10.9	19.2	12.7	49.4	76.8
LSD (5%)					–	0.8	3.3	5.1	6.0	4.0	15.3	–

From Loong *et al.* (1990).

The proportion of the old stand cleared at different periods after replanting is shown. Total yields are given for the old stand from the replanting time until the palms were felled. Yields for the replants are given for 5 production years, and the total FFB yield for each treatment. m = month.

from the old stand, and surpasses the latter within the shortest possible period of time. This involves retaining the potentially productive palms in the old stand until the young palms come into bearing, followed by a gradual removal of the old palms. The latter must be done in such a way that the sum of the annual production from the old and young palms equals at least the annual production obtained from the complete old stand, without affecting, however, the optimum development and production of the young palms.' Ferwerda's ideal procedure may not be achievable in practice, but it provides a target for replanting research.

Two trials were conducted (Ferwerda, 1955) and later summarised by Unilever (1961). In the first trial the old stand was removed 42 months after planting; underplanting gave a yield over 8 years 25% lower than with complete felling before planting, and it was clear that

the old stand had been retained for too long (Table 8.9a). In the second trial, the best total yield (old stand plus replant) was obtained when one-third of the old stand was removed before planting, one-third 1 year after, and the remainder 2 years after that. Yield from this treatment was slightly lower than from the fully planted control in the sixth year after replanting, but by the seventh year there was no difference. This procedure became standard practice in the Congo.

However, underplanting did not find favour in plantations elsewhere, though the method was sometimes used by smallholders. In the 1980s the idea was revived by Nazeeb *et al.* (1988) and Loong *et al.* (1990). Several underplanting treatments gave greater cumulative yields than clean clearing before replanting (Table 8.9b). Yields of the young palms were significantly depressed during the first 3 years of production in most treatments,

but by the fourth year differences had disappeared. The treatment with 50% felling at 6 months and the remainder at 24 months was the highest yielding and the most profitable. A trial in Thailand also showed that this treatment was more profitable than full replanting, and the method is now used widely on a commercial scale (Palat and Corley, 2002). A modification to the method (Loong *et al.*, 1990) was to fell the first 50% of the old stand as alternate pairs of rows, rather than alternate rows (Plate IVA, Table 8.9b). This improved harvester productivity for the old stand (Aminuddin and Ching, 1992). If the palms of the old stand are severely pruned, general felling can be delayed by a few months, and some additional crop can be harvested (Palat and Corley, 2002). These authors found that growth of underplanted palms was depressed for 4 to 5 years after planting, and the yields were lower for 3 years, but overall the total yield was larger with underplanting. The best treatment was again to fell half of the old stand 6 months after underplanting, and to fell the rest at 24 months after underplanting, which gave the optimum balance between depressing the yields of the young palms and losing the yields of the old palms, and this is now being used commercially. Hakim *et al.* (1998) planted young palms between the old palms, in the row. In the first and second years after replanting the old palms were pruned; in the third year felling of old palms in a diagonal direction with an excavator could be done without damage to the young palms. The trunks were left to rot, but there was very little *Oryctes* damage, and *Ganoderma* attack was not common. The seedlings were etiolated, but recovered from this in the fourth year. Hakim *et al.* regarded the method as successful, but there was no direct comparison with other plots replanted after complete felling.

Underplanting has not been used more extensively because it is commonly assumed that it increases *Ganoderma* basal stem rot in the next generation of palms. However, as discussed in Section 12.1.6.3, any such effects are usually quite small, and not sufficient to outweigh the economic benefit of underplanting. Another problem may be the development of *Oryctes* larvae in the old trunks, and subsequent damage to the young palms (see Section 12.2.4.1), but Hakim *et al.* (1998) claimed that this was a manageable problem.

Most planters seem to believe at present that underplanting is not worth the trouble, even if it can be profitable. This is especially so when labour and supervisory staff are in short supply. However, much research has been done on optimising methods of replanting after clean clearing, but underplanting has received little attention. For example, legume covers

were not established in the trials of Loong *et al.* (1990), or of Hakim *et al.* (1998), but if pairs of rows of the old stand are felled, legumes can easily be established in the resulting avenues (Palat and Corley, 2002). Cover crop establishment is easier if the first felling is done before planting, but then 6 months crop from the felled old stand is forgone.

Ablation gives some benefit in underplanting (Chia *et al.*, 2002), probably because it improves root growth (see Section 10.3.2). Nutrient requirements with underplanting have not been studied. Competition from the old stand is likely to increase fertiliser needs, but in practice total inputs may be reduced rather than increased, because applications to the old stand are commonly stopped 1 or 2 years, and sometimes up to 4 years, before replanting (Nazeeb *et al.*, 1995). Teo *et al.* (2000) advised against this practice, and showed that profitable responses to fertiliser application were obtained up to the year before planting. Hakim *et al.* (1998) used large planting holes; roots of the old stand will be cut back when such holes are dug, which may help to reduce competition for nutrients for some time after planting.

There is no doubt that underplanting requires careful management if it is to be successful. Where labour is short, or management inexperienced, clean clearing may be the safer option. A particular practical problem has been that the second felling, scheduled for 24 months, may be delayed, either because of labour shortage, or because high palm oil prices discourage the felling of productive palms. It needs to be remembered that every 6 months' delay in clearing the old stand probably causes a loss of at least 5 t FFB/ha from the young palms (Table 8.9b).

Rao *et al.* (1998) found that the interaction between progeny and the method of replanting was highly significant for later yield and growth. The progenies therefore need selection with special care if underplanting is to be used.

8.3.4.4 Detailed field procedures

See Hartley (1988), Rankine and Fairhurst (1998b) and Jacquemard (1998).

Underbrushing: This is essential when clearing from forest, to give access for labour and allow measurement, lining and perhaps hole-digging. The work is done manually with axes and cutlasses, and may need between 1 and 8 man-days/ha, depending on the density of the vegetation and the quality of the labour.

Lining out: Many methods of lining out have been used. The lining process is described in particular detail by Jacquemard (1998). The main points are that

the palm lines normally run from north to south, and with the usual triangular pattern of planting, the palms in one row stand opposite a space in the adjacent rows. At 143 palms to the hectare, the distance between palms is 9 m, on an equilateral triangle, and the distance between rows is 7.8 m (see Section 9.3.3). Having established a north–south baseline, lines are put out at 60° to this on which the interpalm distances are marked off. Alternatively, the base line can be taken as east–west if the roads are lined up in this way, and the distance between north–south palm lines marked off along this. These methods cannot be used in steep land with terraces, where the terrace itself becomes the baseline.

Holing: The digging of a planting hole of 60 or 90 cm cube size has been traditional in most oil palm areas. This is then filled with topsoil and allowed to settle, and a smaller hole is dug in the centre large enough to take the root mass from the polythene nursery bag. However, it is not clear that this is essential, and it has rarely been tested by experiment, except on peat soils. The digging of a hole rather larger than the polybag may be sufficient (see Section 9.1.2).

Felling: The main problem is with large trees with buttress roots. These are usually felled some 2 m above the ground, and the stumps are left to rot if they are large. On level land trees are felled in the north–south direction, but on steep areas they are best felled along the contour. It is important to place all the debris into alternate lines, or one in three lines, to leave free access. There is still some debate about whether to use tractors for tree felling, or manual labour with chainsaws; in practice, this will often be decided by the availability of labour. Hartley

(1988) considered that the best system was to use chain-saws for the actual felling, and tractors or bulldozers for moving and stacking the tree trunks, but bulldozers are now very widely used for felling the smaller trees.

Cover establishment: Earlier, many plantations, especially in Africa, allowed natural vegetation to grow up, and controlled this by frequent cutting. This could be quite successful, but the uniformity and potential nitrogen fixation of a planted leguminous cover has made this the normal procedure. The sowing is typically done shortly before planting of the palms, especially if the soil has been cultivated so that a reasonable seedbed has been prepared. In West Africa, or other areas with seasonal rains, it may be advisable to plant palms before the rains have fully started, and in that case sowing the cover can be delayed until the heavy rains arrive. Further discussion of covers is presented in Chapter 10.

Costs: The input of machinery and labour is high (Table 8.10); the actual cost will depend on the wage rates for labour.

8.3.5 Hilly land: platforms and terraces

The construction of platforms for the individual palms, (Plate 8.3) or terraces for lines of palms (Plate IVC), is an expensive part of land preparation, but it is very necessary on seriously sloping land. There has been some controversy about the relative merits of these two solutions. On hilly land the horizontal distances are not the same as along the soil surface and, measured along the latter, if the gradient is 1 in 3 the between–palm distance is 5.3% greater than the horizontal distance. Measuring

Table 8.10 Duration of labour and machine inputs in land preparation for planting, per hectare planted

Operation	Man-days	Tractor hours	Materials
New plantation			
Manual or mechanical felling	30–40	–	Axe or chainsaw
Row clearing	6–10	–	Chainsaw
Manual windrowing	45	–	Chainsaw
Mechanical windrowing	2	3–4	Caterpillar tractor ^a
Track opening	0.2	1	Caterpillar tractor ^b
Track levelling	0.2	1	Caterpillar tractor ^c
Burning	1	–	
Replanting			
Manual felling	40–50	–	Axe or chisel
Mechanical felling/windrowing	0.75	1	Caterpillar tractor

After Jacquemard (1998).

^aTractor with Rome KG spur blade.

^bTractor with Rome KG spur blade.

^cAngledozer or leveller.



Plate 8.3 Young palm planted on a platform, and mulched with black polythene sheet. (Photo: Applied Agricultural Research, Malaysia.)

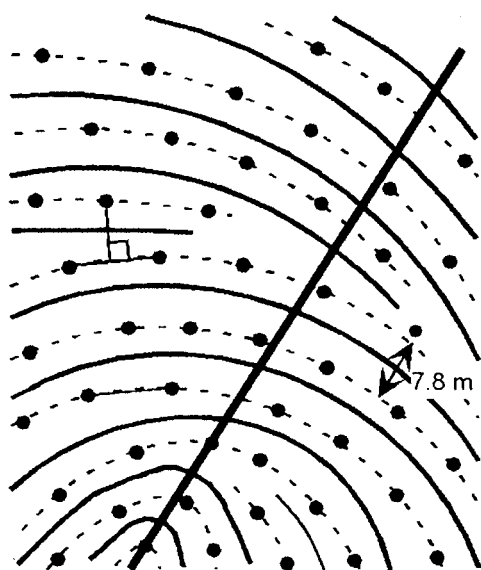


Fig. 8.15 Layout of terraced steep planting land, with terraces following contours, for 143 palms/ha and spacing between palms along contours around 8 m. Dot: planting point; heavy line: line of steepest slope; dotted line: contour; fine line: windrow of felled trees. (After Rankine and Fairhurst, 1998b.)

along the soil surface results in overcrowding of the palms and a distorted triangular pattern. The latter is unavoidable with terraces (Figure 8.15).

Rankine and Fairhurst (1998b) recommended that on slight slopes of less than 6°, there may still be a need for

bunds along the contours to control surface water flow. Often the stacking of cut fronds along the contour is sufficient. In steeper areas of 6–20° slope platforms for the individual palms may be appropriate, whilst keeping the usual planting pattern. In areas with slopes greater than 20° slope terracing is essential; most authors are against using such land at all (Hartley, 1988), and palms should most certainly not be planted where the slope is greater than 40°. The terraces must follow the contours, and if they are wide enough (4–6 m) they also act as harvesting paths that can be used by small in-field harvesting vehicles, if the palms are planted close to the back of the terrace (Plate IVC). With narrower terraces a small, intermediate terrace may be needed for harvesting. The distance between palms D along each terrace is given by:

$$D = 10,000 / (\text{Nominal planting density in palms/ha} \times \text{Distance between terraces}) \quad (8.5)$$

This means that as the land becomes steeper and terraces become closer together, the between-palm distance along the terraces will increase, and vice versa (Figure 8.15). Ballo Koffi and Quencez (1991) have given a detailed exposition of constructing terraces, with a design adapted to control of water in agronomic experiments.

Hartley (1988) concluded firmly that platforms were superior to terraces because palms come into bearing earlier on platforms. This is not unexpected if the palm is planted into infertile subsoil on the inner part of the terrace (Hamdan *et al.*, 2000), which may also be prone

Table 8.11 Vegetative growth of palms planted on terraces or platforms with different systems on a slope

(a) 11 months after planting

	Rachis length (cm)	Total frond (no.)	Frond dry weight (kg)	Petiole cross-section (cm ²)	Leaf area (m ²)	<i>L</i>
System 1	199.7	15	0.63	4.19	1.48	0.34
System 2	208.6	16	0.63	4.17	1.43	0.34
System 3	190.7	16	0.61	3.97	1.38	0.32
System 4	198.5	16	0.62	4.07	1.37	0.29
<i>F</i> -ratio	ns	ns	ns	ns	ns	ns

(b) 21 months after planting

Rachis	Total length (cm)	Total frond (no.)	Petiole weight (kg)	Leaf cross section (cm ²)	Leaf area (m ²)	<i>L</i>
System 1	246.9	20	0.88	6.61	1.87	0.56
System 2	254.9	22	0.96	7.39	1.98	0.63
System 3	223.9	20	0.88	6.67	1.52	0.45
System 4	244.4	19	0.88	6.60	1.70	0.47
<i>F</i> -ratio	ns	ns	ns	ns	ns	ns

After Chee *et al.* (1995).

Mean of two plots with 15 palms/plot.

System 1: palms planted on 4.3 m wide terraces with normal planting holes filled with subsoil; system 2: palms planted on 4.3 m wide terraces with large planting holes filled with topsoil; system 3: palms planted in normal planting holes on 3 m × 3 m platforms on contour with 3-m-wide mechanisation path every two contour palm rows; system 4: palms planted in normal planting holes on 3 m wide terraces with 3 m wide mechanisation path every two terraces.

L: leaf area index; ns: not significant.

to waterlogging. However it may be difficult for harvesters to move along the contour behind the platforms, so that above a certain slope it may be essential to have terraces to give a practical harvesting system. It is not yet clear what is the practical limit to slope set by the increasing use of machinery in the field. Tayeb Dolmat (2000) recommended terraces with slopes greater than 3°, but the length of terrace should not exceed 1000 m/ha, i.e. a 10 m mean distance between terraces.

Chee *et al.* (1995) made a thorough study of this question in two experiments, one in Johore and one in Sabah. Three terracing systems and one platform system were compared on Rengam series soil that was being replanted with palms, on a slope ranging from 18 to 28°. All three terracing systems gave better growth than the platform (Table 8.11, Figure 8.15), the best being terraces of 4.3 m width, using large planting holes filled with topsoil (system 2). The soil moisture was larger in terrace soil than platform soil, taken from the back of each. The costs in the trial on Rengam soil were largest for the platform (system 3), slightly less for terraces with large planting holes (system 2) and smallest with simple terraces with normal holes (system 1).

The other trial, in Sabah, was on a field being replanted with oil palms from cocoa. It was on Tanjung Lipat soil, a stony soil derived from mudstone and sandstone, which was more prone to erosion and slippage than the Rengam. It also had a higher slope, of 18–30°, and a higher rainfall. In general, terracing suffered most from soil slippage, but in both cases well-established leguminous covers appeared to stabilise the system. The treatments were rather different to those given above, but again the best growth was with the terrace treatment, although the differences were small. In this experiment 3 m wide mechanisation paths with no planted palms were used in the platform and one terrace treatment. The initial conclusion of these experiments was that terraces were at least as good as, and probably better than, platforms and this seems to be the consensus.

8.3.6 Preparation of peat soils

Peat soils demand some differences in procedure from mineral soils. These areas will always have high water tables, and it is essential to plan and install the main drains at once. If possible, felling should follow as long

as 1–2 years later, to allow the peat to settle during the draining. It must not be allowed to dry out completely, as it may then become hydrophobic and difficult to rewet. The objective is to have a system that allows the water level to be precisely managed, so that the rate of shrinkage of the peat, which depends on the depth of the water table, can be controlled over periods of many years. It may be necessary to have a drain for every four rows (Rankine and Fairhurst, 1998b). During felling and clearing of the planting avenue it may be necessary to compact the peat deliberately, so as to ensure proper support for the palms. This requires all stumps to be cut off below the peat level, after which compaction is carried out by an excavator running several times over the cleared peat surface. Finally, there should be a 10 m wide strip (i.e. including two palm rows), free of timber and compacted to 1–2 m depth. If this general consolidation is not done, the ‘hole in hole’ planting technique should be used, in which a special tractor attachment compacts the peat over a 2 m², and then punches out a planting hole in the bottom of this area. This can have major effects on the success of the palms (Tayeb Dolmat *et al.*, 1995) (Table 8.12).

Burning is particularly dangerous when clearing peat soils (Nicholas and Bowen, 1999), because of the

possibility of setting fire to the peat itself, or to lignite layers within it. This paper reports on the many large peat fires in South Sumatra in 1997 that helped to blanket the whole area with smoke. It is estimated that one-sixth of the entire wetland area in South Sumatra was affected by fires, many started in the process of land clearing, which could only be extinguished by the arrival of the rains and a rising water table.

Tidal swampy land has been used in the past, and large new areas of this type of land are being opened up in Indonesia (Martoyo and Purba, 1995). These authors reported estates on this type of land with FFB yields of well over 20 t/ha. The listed constraints are as expected, namely low micronutrients and macronutrients, pyrites that may oxidise to sulfate if not carefully managed, salinity and the need for controlled drainage. There are considerable environmental interests in these areas, and many objections to their being used for agriculture (Sargeant, 2001). Earlier work on Carey Island in Malaysia (Toh *et al.*, 1988) described the reclamation of mangrove swamps, with desalination being a major task that should be started 2–3 years before planting is planned. They estimated that the costs of reclamation and establishment at that time were 25–30% larger than in replantings of oil palms on coastal soils, but

Table 8.12 Effect of compaction of peat in planting rows and harvesting paths on bulk density of the peat, and on the vegetative and reproductive growth parameters of the palms

Parameters	Compacted	Uncompacted
Leaning incidence (%)	44.2	71.9
Dead palms due to termite attack (%)	0.83	2.17
Soil		
Bulk density (g/ml)		
Range	0.18–0.27	0.11–0.15
Mean	0.23	0.12
Palm (8 years from planting)		
Vegetative parameters		
Height (m)	2.12	1.81
Girth at 1 m (m)	0.87	0.87
Rachis length		
Frond 17	5.11	4.88
Leaf area (m ²)		
Frond 17	8.67	7.95
Reproductive parameters		
Bunch production/palm per year	21.1	20.7
Average bunch wt (kg)	7.80	7.39
Frond production	25.4	25.2
Sex ratio (%)	74.1	69.3
Floral abortion (%)	4.6	6.3

After Tayeb Dolmat *et al.* (1995).

established plantations are very satisfactory, and the fertiliser requirements are now well understood (Tayeb Dolmat *et al.*, 1996).

8.4 USES AND COVERS OF INTERROWS

8.4.1 General

The partition of light is at the basis of the idea of planting other vegetation under a treecrop. The unused light can be used by a crop or forage plant, so that there is a cash yield even from an early date. It is useful to distinguish between 'establishment intercropping', where the crop is only planted in the first few years, when the palms' shade is still small, and cases where the cropping or grazing goes on indefinitely. In the second case the yield must be very small eventually if the palms grow well and are planted at the usual density. It is possible to plant palms on a different pattern, so that by design the shading will be limited. The yield of the palms will then be reduced, but this may well be acceptable for smallholders.

8.4.2 Leguminous and other covers

The simplest way of utilising the light that is not intercepted by the oil palms is to have a legume creeper cover that helps to prevent erosion and gives only limited competition to the palms. The alternative is the assemblage of weeds and shrubs that grow up naturally. This has the advantages that it is very cheap to produce and it recycles nutrients from the soil. However, it is expensive to keep down, and if it is not controlled, it starts to shade the palms when they are young, or prevent access. There is certainly also competition below ground, and an uncontrolled natural (bush) cover will set back the growth of the palms. Tests of different covers in Nigeria and

Malaysia showed that palms gave the largest yields with bare or cropped soil, presumably because they then had less competition for water or nutrients (Table 8.13) (Hartley, 1988). However, it is little expensive to keep a soil bare unless labour is very cheap, and there is a danger of enhanced erosion; hence, leguminous creepers are usually sown at or about the time of planting of palms. The FFB yields with leguminous covers tend to be rather similar to those with weed (bush) cover, but better in Malaysia. These creepers grow to a limited height, they cover felled vegetation and lessen the threat of *Oryctes* attack, and they almost certainly will fix gaseous nitrogen for their own growth, some of which will become available to the palms (see Section 10.1.2.4, 11.1.4). In some cases climbers such as *Pueraria phaseoloides* or other creepers establish themselves naturally without sowing seed (see Section 10.1.2.3), but establishment of these creepers will always be delayed by soil compaction during land preparation. Goh and Chew (2000) recommended sowing a mixture of seed of *Pueraria javanica*, *Calapogonium mucunoides* and *Calapogonium caeruleum*.

Hartley (1988) summarised the reasons for establishing a good cover soon after the palms were planted:

- the need to prevent competition between palms and other vegetation, by easier ring weeding and control of vegetation height;
- the need for a cover that extends rapidly and requires little maintenance, to protect the soil from erosion (Pushparajah, 1983);
- the need for a cover that will require minimal attention in the areas that become mature, and that includes no harmful species;
- the need for a cover that helps to maintain fertility, especially by fixing nitrogen.

The long history of debate over cover policy is given by Hartley (1988). There appear to be differences

Table 8.13 Effects on FFB yield of palms growing with natural cover, *Pueraria* cover and different food intercropping systems during early growth, in Congo and Nigeria

Interpalm treatment	Congo			Nigeria		
	3rd year	16th year	16 years	1st–3rd year	14th–19th year	19 years average
Control (<i>Pueraria</i>)	100	100	100	100	100	100
Natural cover	–	–	–	103	94	96
Two years' food cropping	125	105	117	108	88	95
Cropping 'to exhaustion'	–	–	–	120	89	98
Three years' bananas	124	100	113	–	–	–

After Hartley (1988).

between West Africa and Malaysia in that natural cover has been considered superior to legumes in the former. The legumes established slowly, but later were so vigorous that they competed with palms. Conversely, experience in Malaysia always favoured legume creepers, even though they establish rather less easily than in West Africa (Hartley, 1988) (see Chapter 10).

It is likely that legumes contribute extra nitrogen to the system, including the palms (Chan and Lim, 1982; Agamuthu and Broughton, 1985). Vesterager *et al.* (1995) tested the effects of different levels of *Pueraria* litter on the nitrogen fixation of young *Pueraria* plants grown in pots. The plants grew larger by 26% with litter, as against no litter, and the nitrogen fixed was directly related to the amount of litter supplied.

8.4.3 Agricultural uses of interrows

8.4.3.1 Establishment intercropping

This is intercropping for a limited number of years, below young palms that are planted at normal densities, and that are expected to continue as a normal plantation when the cropping ceases (Table 8.13, Plate 8.4). Several early trials of this have been carried out in Africa. In the Congo, 1, 2 and 3 years of cropping after planting (Hartley, 1988) produced no subsequent deleterious effects up to 16 years after planting. A similar trial planted on forest land near Benin City in Nigeria in 1940

included cropping for 2 years, and also for as long as cropping remained possible. This early treatment used maize, yams and cassava, with the shade-resistant cocoyam as the only crop up until 12 years (Plate 8.4). For the first 2 or 3 years on the cropped plots good yields from crops and growth from palms were obtained. For up to 16 years after planting there were no signs of poorer growth on the intercropped plots, although later FFB yields on these plots tended to decrease a little (Sparnaaij, 1957). Soil studies on these plots showed a slight decrease in chemical fertility, especially lower cation content, below that under natural cover; the leguminous cover was intermediate (Tinker, 1963). As fertility was not higher on intercropped plots, the reason for better palm yields must have been the reduced competition for water and nutrients.

Good results were also obtained for cocoyam (*Xanthosoma sagittifolium*) in a more recent experiment near Benin City, in the fifth and sixth years after planting (Salako *et al.*, 1995; Erhabor and Filson, 1999). The yield of both cocoyam and FFB was well up to local expectations. The yields of both were higher on the interlines with windrows than on the ones left empty, suggesting that nutrient deficiency was restricting the yields, and that more fertiliser should have been tested. The changes in the soil fertility during and at the end of an intercropping system based on oil palms were found to be acceptable. It was concluded that intercropping with cocoyam was successful for at least the first 5 years.



Plate 8.4 Establishment intercropping: young palms growing between lines of yams (*Dioscorea* sp.) in Nigeria.

Okpala-Jose (1995) made a detailed study of intercropping oil palms with cassava in Nigeria. There was a general shading effect due to the cassava, which varied with the nearest distance of cassava plants from the palms. If this distance exceeded 2.3 m, the yield from the intercropped palms was greater than that from palms as a sole crop, probably owing to less competition, on the assumption that the uncropped soil around the palms was bare. The yields of cassava were not given, so it is not possible to determine whether the enterprise was successful.

Erhabor and Filson (1999) tested oil palm, maize, soya bean and cocoyam against a series of different combinations of these crops to determine the soil changes that resulted. There was little change in pH, but soil organic matter and nitrogen declined drastically in some treatments, but not together. Potassium declined in some treatments by more than half, but phosphate increased strongly in one treatment. The changes were so sharp and so irregular that they need verification.

8.4.3.2 Permanent arable cropping

In the wild palm groves of West Africa shifting cultivation is practised around the palms, but it cannot usually be called permanent cropping. There is little information on the results, for both crop and palms, of applying fertiliser and other inputs. Such cash investments may be inefficient with low-yielding wild palm material. Intercropping under planted palms is more promising (Hårdter *et al.*, 1997). This demands that palms are more widely spaced than in the typical plantation, as the yield from the intercrop is seen as having comparable importance to the palm yield.

Such cropping is best described as agroforestry. For reasons that are not obvious, professional agroforesters in the past tended to focus solely on trees that are not well-known tree crops, but are believed to act as soil improvers, or to provide fodder for livestock (Huxley, 1999). However, in more recent times several publications have appeared on intercropping of oil palms, though the conclusions are still debatable. There is reason to use a tree crop with known high yield of a product that is easily saleable, and that thereby diversifies the farmer's income. There is also a much clearer concept of an oil palm plantation as an ecosystem in its own right, which may be modified by the presence of other plant and animal species (Last, 2001). Current interest in sustainable farming has also led to various studies of the principles of intercropping. Wainwright (1995) studied methods of measuring the light distribution near to ground level as a basis for devising intercropping

systems. Salako *et al.* (2001) tested the effects of various cover plants on the physical soil fertility of a degraded alfisol in south-west Nigeria, without a tree crop being present. They tried well-known fallows (*Pueraria*, *Senna*, *Leucaena*), natural fallow and maize. The soil properties improved under all the fallows, with *Pueraria* and natural fallow giving the largest improvements in bulk density, which decreased from 1.56 g/cm³ to 1.11 g/cm³. However, the improvement was fragile and easily degraded under cropping.

The main problem under continuous food intercropping is with erosion, because the tilled soil is there for a long period, rather than the 2–3 years of establishment intercropping, or shifting cultivation. This was studied by Hamel (1986) in connection with the Ivory Coast food sufficiency programme, using the Wischmeier and Smith generalised erosion equation. This is a simple multiplicative equation stated as:

$$E = R \times K \times m f(SL) \times C \times P \quad (8.6)$$

where E is a measure of soil erosion, R is an index of climatic aggressivity, K is the coefficient of erodibility of the bare soil, $m f(SL)$ is a function of topography, C is a measure of cultivation effects, and P is a measure of the antierosion measures undertaken.

There was no physical validation of the results of applying the equation, so it is uncertain whether the chosen values of the parameters in the equation were correct. The paper suggested that the results should only be used in a comparative way. Under West African conditions the cultivation of food crops in the interlines caused a serious erosion hazard, and there were some food crops that should not have been used at all on sloping sites. The factor C in Equation 8.6 deals with plant cover/crop techniques. Some values of C are of interest: bare soil, 1.0; rapidly growing cover crop, 0.1–0.01; maize, millet, etc., 0.4–0.9; cassava, 0.2–0.8; oil palm with cover plants, 0.001–0.3. The considerable potential resistance to erosion in an oil palm plantation is notable, but the wide range of this factor indicates that poor agronomy can lead to serious erosion even in this situation.

Some experiments in Nigeria (Sparnaaij 1957) tested the results of food intercropping. The spacing of palms was varied, and it was found that wide rows, with palms close together in the rows to give the normal density, gave lower yields than the normal spacing. With wide rows and normal spacing in the rows, each palm gave a slightly higher yield than with a normal triangular arrangement, as would be expected. Food crops kept 3.7 m away from the palm bases had no effect on the yield of the latter.

Fifteen years after the experiments started the yield of the half-density palm plots was two-thirds that of normal-density plots. Dry-season cropping increased yields in the previously forested area up to the 11th year from planting, while the good effects of early intercropping lasted for 7 years in the previously farmed area and for 13 years in the former palm grove area. Satisfactory food crops were obtained from the wide interlines. The best means of combining the two crops seemed to be alternating normally spaced double rows, with gaps similar in size between them.

8.4.3.3 Other treecrops

There has been considerable interest in using mixed treecrops (Hartley, 1988). Rubber and oil palm were planted together in the early years of oil palm cultivation in Indonesia. However, these crops are not compatible in the long run, as the rubber overtops and shades the oil palm. In such a mixture the rubber will be too widely spaced, and so give low yields per hectare, and the shaded oil palms will also give poor yields.

Coffee and cocoa are small trees, and can be planted with oil palms. Indeed, cocoa benefits from light shade in most circumstances, although the shade cast by mature oil palms may be too intense. However, both trees, especially the cocoa, are more demanding of the soil than is the oil palm, and do not grow well on the soils developed on Tertiary sands. The good cocoa soils of Ghana and western Nigeria can grow cocoa well with palm, but there seems little reason to share these good soils with oil palms. Robusta coffee is less demanding, and will grow on the Congo river basin, or the soils on the Tertiary sands of West Africa. Robusta coffee will grow well in many parts of South-east Asia, but it is less profitable than oil palm.

On the coastal alluvium of Malaysia coconuts mixed with cocoa have been popular for many years, and it seemed possible that a similar mixture with oil palms might become popular, although the heavier shade of the palms is a great disadvantage. The planting pattern can be simple, replacing one-seventh, one-quarter or one-third of the palms, which leaves convenient spaces for the cocoa, and the one-quarter thinning allowed 648 cocoa trees/ha, and yields of 500–700 kg/ha dry cocoa. This interplanting is therefore probably profitable, but it is now rarely used in practice.

More recently, Wessel (1992) reviewed palm/cocoa production systems and their use for agroforestry in West Africa, both in smallholder plots and in large plantations. Lee and Kasbi (1980) tested various spatial single-row combinations of oil palms and cocoa in

Malaysia. The best treatment was single-row palms at 10×7 m (143 palms/ha) and single-row cocoa at 10×2.5 m (400 trees/ha). Oil palms in this system yielded at the same rate as in monocrop palm plantings. The yield of cocoa seemed to vary linearly with the density of trees. Amoah *et al.* (1995) tested underplanting of cocoa under oil palms in Ghana. There were three triangular spacings of mature oil palms, at 8.7, 9.9 and 10.5 m. Cocoa was underplanted at a spacing of 2.4 m. There were no effects on the yields of the palms, but cocoa growth and yield were significantly better at an oil palm spacing of 9.9 or 10.5 than at 8.7 m. It is not clear whether the yield was economically viable. Ekanade (1998) also studied the layout of palms and cocoa, and found that a 'hollow square' was more efficient than a linear layout with two rows of oil palms to one of cocoa. He found that several soil parameters were better under mixed than under sole crops.

It seems that mixed tree plantings are possible and may be successful. The main drawback recently has been the low price of cocoa, so that it pays to plant oil palms at full normal density, rather than share some of the space with cocoa. It seems essential for there to be some proven advantage from growing mixed treecrops before they will be adopted on a large scale. Throughout agriculture the practical management advantages of growing monocrops have led to the almost universal adoption of these for successful high-output farming. The theory of mixed cropping suggests that it should be most successful where the two crops use light and soil resources in different ways, so that the total resources are tapped more efficiently than with one crop alone. On this theory, the interplanting of similar treecrops would not be promising.

8.4.3.4 Grazing regimes

Stock grazing is rarely practicable under well-grown adult trees with heavy crowns and a dense shade. However, grazing is practicable in the early years, or under palms that have very light crowns, or that have been planted at a lower density than normal. Amongst recent work, Fawzi *et al.* (1998) conducted a purely economic desk study and concluded that cattle grazing under palms could be profitable. They assumed, on the basis of past work, that the yields of the palms were not affected by the grazing, possibly because the export of nutrients in cattle products would be small. Wong (1998) used an ongoing trial on cattle stocking rate under oil palms to experiment on the compaction caused by the grazing treatments. Grazing of cattle at all rates of stocking significantly increased soil

compaction in the top 20 cm layer, and this had a detrimental effect on the root growth of the palms. In the Peruvian Amazon region Portillo (1994) tested planting a crop of rice first, after which oil palm seedlings were planted. *Stylosanthes guianensis* was planted in the interrows and used to feed dairy cattle for several years until income from the oil palms built up. A simulation model of integrated crop–livestock farming has been published (Dahlan and Shahar, 1992).

Zainudin *et al.* (2000) discussed grazing of beef cattle under palms, one objective being to control maintenance costs by grazing down the plant cover. This gave a saving of around 30% when it was tested on a 1000 ha estate; presumably this would also apply to smallholder plots. Grazing was mainly on herbaceous plants and, after grazing, herbicide spraying had to be used to control woody plants and growth within the palm circles. If grazing started before the palms were 5–7 years old the cattle damaged the palms by grazing their fronds. The local variety of cattle was highly suitable, but the sale of the beef needed a better marketing system. Chen and Baker (1993) provided very detailed information about forage produced under treecrops. They found that native species yielded well compared with improved forages, and that three Kedah–Kelantan cattle per hectare could be supported. The combined system resisted erosion more than either trees or forages alone. Forage yields declined from 3–4.8 t dry matter/ha under immature palms to 0.1–1.0 t/ha under mature ones, but trees grew better under these systems than under normally controlled covers. Ariff Omar (1999) considered that both palms and cattle could be useful commercial enterprises over the period of 4–10 years after palm planting, and recommended grazing in this way. Haji Baba *et al.* (1998) has also reported on growth and reproduction of small ruminants successfully kept in a livestock–oil palm system.

Most work with cattle has been research or on a small scale. Mann *et al.* (2002) reported a larger-scale

operation in New Britain Palm Oil Ltd, in which cattle rotationally grazed a half-stand of palms (505 ha) and pure pasture (159 ha), after which they were finished in a 1000 head feedlot. Butchering and retail sale were on site. Grazing started from the time of planting, and provided cash flow from the beginning. The operation over the lifetime of the palms is expected to be 78% as profitable as full oil palms, but the cattle provide a useful diversified source of income.

Grazing with sheep has also been investigated (Wattanachant *et al.*, 1997) and mathematical models of sheep growth were developed. The daily gain was only around 50 g/day per sheep, probably because of the limited grazing period and poor quality of herbage under adult palms of 9–21 years. Wattanachant *et al.* (2001) investigated the type and quality of the ground cover, most of the vegetation being grass. The sheep preferred grass, broadleaved plants, legumes, oil palm seedlings and ferns, in that order. The study appears to have been rather academic, and concluded that sheep required the feeding of concentrates when grazing under oil palms.

The exploitation of the interrows on an estate may give little dependable gain because of the labour and capital costs and additional managerial complexity, despite the conclusions of Zainudin *et al.* (2000) and Chen and Baker (1993). However, it would be good if an estate tested these grazing systems on a whole-field scale. Smallholders should find that these systems provide a useful enterprise, although it will require a more detailed level of management than is normally necessary for either separate oil palms or grazing to make it a success. The farmer therefore has to be skilled and energetic. Unfortunately, experience is that smallholders' oil palm plots are less well maintained than those on estates. Present practical information on this subject seems to be inadequate.

Chapter 9

The Establishment of Oil Palms in the Field

In planting oil palms in the field, the first objective is to bring them into bearing as early as possible and so to reduce the period in which no return on capital outlay is being obtained. Growth to the bearing stage can be influenced at planting time by:

- the stage of development and the general health of the nursery seedling
- the method of transplanting
- the time of transplanting.

The second objective is to space the plants in the field so that the optimum economic yield will be obtained from the whole period of production. Both objectives are covered in this chapter. Before transplanting, thorough culling, to remove abnormal plants, is essential. This is discussed in Chapter 7.

9.1 PLANTING IN THE FIELD

9.1.1 Stage of seedling development

The right age to transplant is determined by balancing a number of factors. Small seedlings cost less to transplant and should show little check in growth, but they will be more uneven owing to greater susceptibility to pests, and perhaps because culling of young plants is less efficient; weeding costs will be greater, and they will take longer to come into bearing. Older seedlings are more costly to transplant and are subject to a greater initial check, but nevertheless they come into bearing earlier. It may be that there is little difference in the time from germination to the start of production, but it must be remembered that the greatest 'cost' in a replant is the loss of crop from the old stand. In financial terms, the main costs of a replant start when the old stand is felled, so extra expenditure in the nursery, to reduce the non-productive period in the field, will often be worthwhile (Section 9.2). When these factors are all taken into account it will usually be found inadvisable to transplant seedlings younger than about 10 months or older than about 20 months from the germinated seed stage.

In regions with no distinct dry season it is preferable to plant well-developed seedlings which have been growing in the nursery for 10–16 months. Early experiments in Malaysia showed that 14–20-month-old seedlings came into bearing earlier and gave appreciably higher early yields than palms only 8 months old (Gray and Hew, 1963–1996), and that polybag seedlings transplanted at 13 months or older give significantly higher yields in the first 3 bearing years than seedlings transplanted at younger ages (Hew and Tam, 1971). Other experiments showed that older seedlings maintained a higher leaf production rate, came into bearing earlier, and had heavier bunches, a higher fruit/bunch (F/B) ratio and, perhaps most importantly, a higher oil to mesocarp in the first year of harvesting (Khoo and Chew, 1977). The growth of older palms may be checked after planting, the first leaves to be opened being shorter than the last leaves opened in the nursery, but this tendency can be reduced by good transplanting techniques and is reversed soon enough for the older seedlings to maintain a lead over the younger ones.

9.1.2 Method of transplanting

Seedlings in polythene bags should be well watered the day before transplanting and, if necessary, fungicide and insecticide treatment can be given. The preparation of the planting site has been described in Chapter 8. At the time of planting a hole is dug with a diameter slightly wider than that of the polybag. The base of the bag is then cut away and the whole plant in the bag is placed in the hole. The side of the bag may then be slit and the bag pulled out leaving the roots with soil intact. The small gap between the root ball and the surrounding ground is then filled with topsoil, which is firmly pressed in with the feet or some implement. This is a very important operation as the plant must be firm in the ground, but the young roots must be able to enter the surrounding soil without delay or hindrance. Unless seedlings are planted firmly they are in danger of being blown over by high winds before their root systems are fully established in the soil. It is also important that the seedling should be planted so that

the stem base is not below the level of the ground. Deep planting has been shown to retard subsequent growth (WAIFOR, 1955), and may be a particular problem if the growing point is below ground level and temporary waterlogging occurs after heavy rain.

The use of much larger planting holes has been advocated in Malaysia, but there is little experimental evidence to support this. Zambri and Zin (1995) described the use of holes 1–1.2 m deep by 1.2–1.8 m across; these were refilled with topsoil, in one case mixed with empty fruit bunches (EFB). The palms were planted in a standard-sized hole in the centre, and mulched with EFB after planting. There was a possible improvement in vegetative growth, and earlier flowering, but it was not clear whether the comparison was replicated. Yield data were presented without a standard for comparison, so cannot be judged. Given that EFB mulching is known to be beneficial (Section 9.1.4.1), it was not clear from this work that the large hole gave any benefit. However, in poor soils a large hole might be expected to help with rapid establishment of a good root system, and thus to improve survival in areas with a severe dry season. Large holes may also be useful in underplantings.

With very large 12–18-month-old seedlings it may be necessary to prune the leaves to make handling easier when transplanting. This is mainly done for convenience, there being little evidence that it has a positive effect. Trials in Nigeria showed that seedlings 1.5 m high could have their leaves cut back to about 1 m without affecting subsequent growth (Gunn and Sheldrick, 1963). In the Ivory Coast it was considered that the advent of the polybag nursery had made pruning generally unnecessary, but that some of the older leaves, especially if prematurely withered by *Cercospora*, could be severed at the point of the lowest leaflet insertion and the cut painted with grease to prevent attack by the weevil, *Temnoschoita* sp. (Barnabe, 1976).

9.1.3 Time of transplanting

In regions where there is no very distinct dry season it is possible to plant all the year round, although it is more usual to choose those months in which the average rainfall is high. In the south of Malaysia, for instance, some estates start to plant during April (a month with a comparatively high average rainfall) and continue right through the drier months of June and July into the second wetter season of September to December. Experience has shown that the weather at planting time is not of the first importance; even if rainfall is delayed for 10 days or more after planting,

seedlings correctly planted will survive and rapidly establish themselves with the onset of a rainy period. A great deal of the ‘waiting for rain’, which is a common feature of the planting sequence, is unnecessary, and it is better for the plant to be in the ground when rain comes than for it to be planted during or just after a period of torrential rain.

Nevertheless, in most regions near the equator, where there are two wetter seasons (e.g. in Congo and Malaysia, one in April and May and the other from August to October or November), it is best to choose the beginning of one of these periods for planting out. Even in a typical equatorial climate young seedlings may be retarded by periods of drought, especially in very permeable soils or in those clay soils that tend to bake hard, and it is therefore best to allow for a period of establishment in wet weather before a dry period is expected. The most severely retarded seedlings will be those planted in wet weather just before the drought period sets in.

In the seasonal climate of West Africa the time of planting becomes of much greater importance, the main consideration being to enable the plant to establish itself and grow to the maximum extent possible before the dry season begins. As a general axiom for all countries it may be said that it is better to transplant just before a period of intermittent rain and sunshine is normally experienced rather than to wait for more continuous rain to set in, and that planting late in a wet season should be avoided. However, the situation sometimes arises where planting is unavoidably delayed until towards the end of the rainy season. The question then is whether it is better to plant seedlings of about the right age anyway, or to hold them in the nursery until the next wet season. By then, they will be overgrown, but they can be irrigated in the nursery, whereas this is usually not possible in the field. Results of a trial in Congo (N. Luyindula, unpubl.) showed that yield in the first year of production was better from palms planted at the beginning of the dry season than from overaged palms planted at the beginning of the following wet season. After the first year, there were no further differences in yield.

9.1.4 Cultural practices at transplanting

9.1.4.1 Cultivation and mulching

The site of the planting hole should be cleared of all vegetation to a radius of 1 m and levelled before planting. In the Ivory Coast, mulching with a circle of cut vegetation or with a 1.3 m square piece of perforated

black polythene sheeting was recommended (Dekester, 1962, Plate 8.4). In Nigeria two experiments showed that mulching with cut vegetation or with black polythene improved early growth. The latter appeared to have a slightly greater effect in the first year, but if mulching was continued the mulch of cut vegetation seemed to give an advantage (Sly and Sheldrick, 1965).

Apart from cut vegetation and black polythene, bunch stalks (EFB) have been used as a mulch. EFB is particularly beneficial, because of its nutrient content in addition to the mulch effect. Loong *et al.* (1988) recorded a 16% improvement in yield over the first 2 years of production following EFB mulching. Mulching of older palms is also worthwhile (see Chapter 10). Lim K.N. *et al.* (1995) compared mulching with EFB or with trunk chippings from the old stand: chippings were cheaper because there were no transport costs, and gave marginally (but not significantly) better vegetative growth during the immature period. No yield data were presented, but it appears sensible to use chippings in this way, from the viewpoint of nutrient recycling (see Chapter 11).

In Congo, N. Luyindula (unpubl.) observed a significant increase in leaf area and rachis length after EFB mulching of young palms; there was a 17% increase in yield in the first year of production, but only a small effect thereafter. In general, though, in areas where *Fusarium* wilt is a problem, mulching with EFB may not be advisable, as Renard and de Franqueville (1991) found a significant increase in wilt incidence in plots mulched with EFB.

In areas where the soil is very impermeable and young palms suffer from flooding during periods of heavy rain, improvement through the construction of raised platforms or terraces before planting has been claimed (Poncelet, 1965; Ollagnier and Delvaux, 1966). It should be realised that these measures cannot replace a proper drainage system, although they may be justified in special circumstances. In Colombia, platforms about 1 m in diameter and of varying height have been employed, the small drain around the platform being connected with the interline drains (Hartley, 1988).

9.1.4.2 Manuring at planting

Nitrogen is almost always required during the establishment of oil palms in the field, but there is a danger, which was particularly noticeable in West Africa in the days of field nurseries, of damaging the root system if nitrogen fertilisers are wrongly applied. Several cases have been recorded of deaths following application

of fertilisers, particularly ammonium sulfate, in the planting hole before or at planting time; on other occasions leaves turned pale and dried up prematurely (Sparnaaij and Gunn, 1959). The severity of the effect was increased if there was a dry period immediately after planting.

It is a common practice in Malaysia, taken over from the rubber industry, to apply 200 g of rock phosphate in the planting hole; there is little evidence that this practice is of value, however. Whether phosphorus will be required before the palms come into bearing will depend on the soil. Both potassium and magnesium may be required in young plantings. Where required, applications of potassium have been shown to bring palms earlier into bearing. Magnesium deficiency may occur on certain soils and is accentuated by nitrogen and potassium dressings. Where magnesium is likely to be deficient, it may be added at the rate of 100 g anhydrous magnesium sulfate or 200 g Kieserite/palm.

The most usual need is for nitrogen and potassium; ammonium sulfate and potassium sulfate or chloride may be applied in a ring around the seedling at the rate of 200 g each per palm, 4–6 weeks after planting. In areas requiring higher nitrogen applications the ammonium sulfate dose may be repeated after 5 or 6 months.

9.1.4.3 Protection from rodents

In Africa, damage to young transplanted seedlings by the large rodent, the 'cutting grass', *Thryonomys swinderianus*, may be very serious. This animal is usually present in primary and secondary forest, and if a new planting is adjacent, the cutting grass will attack seedlings up to 3 years from planting. It eats through the leaf base to get at the heart of the plant, and the single apical bud is therefore almost always destroyed and the plant dies. A new planting may be almost totally destroyed by these rodents. The only really effective measure against this destruction is to surround the young plant immediately after planting with a collar of wire netting. Painting the base of the seedlings with tar is not effective (Hartley, 1988).

Owing to the rapidity with which young plants grow it may be necessary to provide wire collars of two different sizes:

- at planting time: height 45 cm, circumference 75 cm
- after 12–18 months: height 60 cm, circumference 120 cm.

Depending on the size of the transplanted palms, collars 45–60 cm in height and 120 cm in circumference may be satisfactory for the whole period. They may be removed between 2 and 3 years after planting, depending on the speed of growth of the seedlings.

In Malaysia, rats (*Rattus tiomanicus* and *R. argentiventer*) and squirrels may damage young palms (Wood, 1976b). These can be controlled by baiting, or the palms protected with wire netting as described above. Porcupines may also destroy young palms (Wood, 1976b), but no control measures have been described.

9.1.5 Replacement of missing palms

With polybag nurseries, transplanting techniques have reached a standard such that seedlings should seldom require replacement. In large, well-regulated plantings the amount of replacement required after 1 year should be only of the order of 0.5%, although in areas with a very severe dry season rather higher replacement, up to 3%, may be needed.

Growth of polybag seedlings after transplanting to the field is usually so rapid that replacement of missing palms (commonly known as ‘supplying’) even 1 year after planting is of doubtful utility, and after 2 years is effectively useless. Palms from the nursery, even an advanced planting material (APM) nursery, will be less well developed than palms of the same age in the field. This, together with an inevitable degree of transplanting shock, will mean that they are overshadowed by their neighbours, and experience shows that they never catch up, and their eventual yield is poor. Thus, it is best to pay attention to replacements shortly after planting rather than to let a year go by before taking any action. In seasonal climates, if planting has been done early enough in the wet season, it is possible to have all stands inspected about a month after planting; any plants that have clearly not established or have been severely attacked by pests can then be replaced before the season is too advanced for planting. In non-seasonal climates, too, it is best to carry out an inspection 1 or 2 months after planting with a view to replacing any dead or doubtful plants before their neighbours have developed so far that replacements will later become permanently retarded. When there are two ‘wetter’ seasons it may be best to leave this first replacement round until just before the next period of heavy rainfall is expected (Lafaille and Daniel, 1965).

Even when such early replacement is done, a further round may be required 1 year after planting, particularly if palms have suffered insect or other damage. In

this case the plants used should be from a new nursery having seedlings of suitable size for transplanting, or from an APM nursery set up specifically for the purpose.

Yeow *et al.* (1982) showed that palms that fail to produce female inflorescences in their first 30 months remain poor yielders for at least the first 4 years of production. They suggested that low yielders could be detected early on from their failure to produce female inflorescences, and then be replaced by specially raised nursery seedlings of the same age. However, they did not demonstrate the practicality of this. As the first female flowers are not normally produced until at least 18 months after planting, replacement will inevitably be much later than recommended above. Thus, it is doubtful whether the cost–benefit analysis done by Yeow *et al.* was valid. One possible way to achieve their objective might be with the APM field nursery and ‘tree spade’ transplanter mentioned by Nazeeb *et al.* (1993) (Section 9.2.1).

9.2 SHORTENING THE IMMATURE PERIOD

A plantation receives no income from a young planting until the start of harvesting. For a new clearing, this delay affects the financial return on the investment. When replanting, it means that plantation infrastructure (transport, mill) may be underutilised. Minimising the immature period between planting and the start of harvesting is desirable, therefore, and has been approached in three different ways. The first (applicable only to replants) is underplanting: the young palms are planted before the old stand is cleared (see Section 8.3.4.3). The second is to use APM, i.e. plants held in the nursery for longer than normal, so that they are better developed at the time of transplanting. The third approach is simply to optimise conventional management techniques (fertilisers, cover crop, mulching), so that the palms develop as quickly as possible. The conventional management of young palms is covered in Chapter 10.

9.2.1 Advanced planting material

Nursery management of APM is discussed in Section 7.2.3. As noted there, it is essential that the nursery be widely spaced, with polybags larger than normal. Simply holding palms in a standard nursery for longer does not produce advanced planting material, and it has

been shown that yield in the first 2 years from such delayed plantings may be 15–40% below that from palms planted at the correct age (Khoo and Chew, 1977; Nazeeb, 1997).

Hashim *et al.* (1988a) found that harvesting of APM material started 5 months earlier than for normal nursery material. Nazeeb *et al.* (1993) found that the shortest period to harvesting with palms in large polybags was 20 months, but the APM bags in their trial weighed nearly 100 kg, and handling presented great practical difficulties. Mechanical handling was restricted by the lack of a prime mover that could enter the field in wet weather (when planting is best done), without risk of getting stuck or of seriously disturbing the soil surface.

Nazeeb *et al.* (1993) also investigated the use of a tractor-mounted ‘tree spade’ to dig up and transplant even more advanced material, from wide-spaced field nurseries located in the fields to be replanted. A period of as little as 12 months from planting to start of harvesting was demonstrated, and Nazeeb *et al.* (1996) obtained yields 57% greater than from standard planting material (an additional 14 t FFB/ha) over the period 17–52 months after planting. However, the machine worked slowly (5–6 palms/h), costs were high, and puddling and soil compaction could be a serious problem, particularly around the field nursery sites.

It appears that the widespread use of APM may not be practicable, therefore. Underplanting looks a more promising way of shortening the immature period (see Section 8.3.4.3), and APM did not give much benefit when combined with underplanting (Nazeeb *et al.*, 1996; Palat and Corley, 2002). The best use for APM may be for replacement palms, where their large size may allow them to catch up with the original planting (Section 9.1.5). As noted above, though, even with APM any replacements should be planted within the first year.

9.3 SPACING OF PLANTS IN THE FIELD

The optimum planting density can only be determined by a knowledge of the potential yield of palms at different spacings (Plate 9.1). When plantations were first established, in the absence of such knowledge, spacing was determined by judging the probable spread of the leaves under plantation conditions. Spacings adopted varied from 7.5 to 10 m, and a triangular arrangement was usually employed, giving between 115 and 205 palms/ha (Hartley, 1988). In most crops yield shows a fairly broad plateau across a range of plant densities, so there is no precise optimum. This is also true of oil palms, although because palms are less flexible in their

growth pattern than dicotyledonous trees, spacing is probably rather more critical than in most tree crops.

9.3.1 Effects of plant spacing on growth and yield

As shown in Chapter 4, closer planting improves light interception and increases total dry matter production by the crop. However, closer planting decreases dry matter production per palm, because of increasing inter-palm competition. Because vegetative dry matter requirements tend to remain constant per palm (see Chapter 4), any reduction in total production will be at the expense of yield. Up to a point, the decrease in yield per palm will be more than compensated for by the increasing number of palms per hectare, so that yield per hectare rises, even though yield per palm falls. Beyond the optimum, however, yield per hectare starts to decrease; this is illustrated in Fig. 4.8.

Breure studied a spacing trial in Papua New Guinea (PNG) in considerable detail (Breure, 1977, 1988a, b; Breure *et al.*, 1990). The trial included palms planted at 56/ha. As Table 9.1 shows, yield per palm at this density and at 110 palms/ha were approximately equal at 5–6 years after planting, indicating that inter-palm competition for light, water or nutrients was not a factor at these densities at that age. In older plants at 56 palms/ha, yield and dry matter production relative to mean leaf area were the same as they had been at 5–6 years. This suggests that competition was still not affecting the lowest density at that age. The data for the 56 palms/ha treatment in Table 9.1 thus give an indication of palm performance without competition.

Mean bunch weight increased with age at all spacings, but the increase between 5–6 and 12–14 years was 92% at 56 palms/ha, but only 54% at 186 palms/ha; there was a clear declining trend in bunch weight with increasing density in the later period, but only a slight decline in the younger palms. Thus, competition appears to restrict the full expression of potential bunch weight.

Bunch number per palm at 5–6 years was only affected by the highest density, but by 12–14 years it was affected at 110 palms/ha. Bunch number decreased with age even at the lowest density, so the age trend normally seen is not simply due to increasing inter-palm competition. However, the decrease with age was greater (60%) at the two highest densities than at the lowest (40%), indicating that both competition and age contribute to the decline normally seen. At 5–6 years, the effect of density on bunch number was

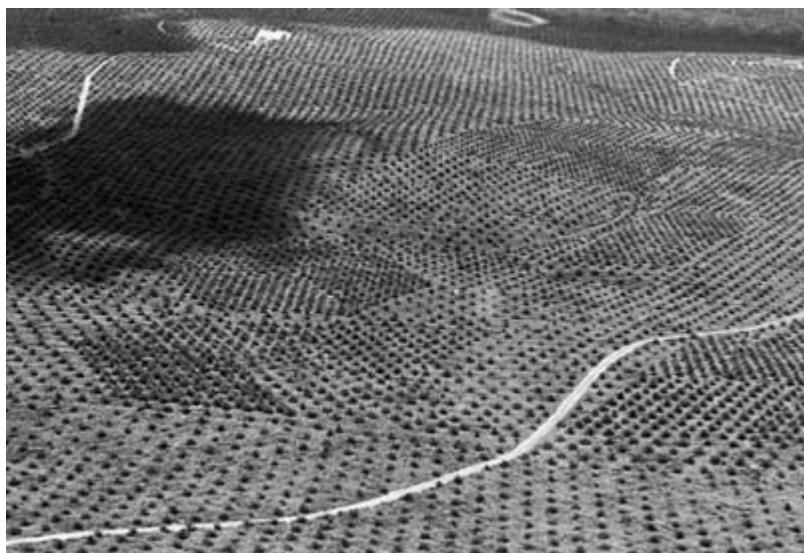


Plate 9.1 An aerial view of a large spacing experiment in Malaysia.

Table 9.1 Effects of planting density on growth and yield in Papua New Guinea.

	Palm age (years)	Planting density (palms/ha)			
		56	110	148	186
Yield of fruit (kg/palm per year)	5–6	256	268	235	179
Yield of fruit (t/ha per year)	5–6	14.3	29.5	34.8	33.3
Oil/bunch (%) ^a	5	–	26.7	26.8	26.9
Vegetative DM (kg/palm per year)	5–6	107	105	101	100
Total DM production (kg/palm per year) ^b	5–6	318	325	294	247
Mean leaf area (m ² /palm) ^c	5–6	280	300	304	304
Yield/leaf area (kg FFB/m ²)	5–6	0.91	0.89	0.77	0.59
DM production/leaf area (kg/m ²)	5–6	1.14	1.08	0.96	0.81
Bunch no. per palm per year	5–6	21.0	20.7	20.0	15.8
Sex ratio (% female)	5–6	59	56	51	42
Abortion rate (%)	5–6	4	10	16	19
Mean bunch weight (kg)	5–6	12.2	12.9	11.8	11.3
Yield of fruit (kg/palm per year)	12–14	301	227	148	114
Yield of fruit (t/ha per year)	12–14	16.9	25.0	21.9	21.2
Oil/bunch (%) ^a	14–15	26.4	27.1	27.7	27.5
Vegetative DM (kg/palm per year)	12–14	135	126	114	115
Total DM production (kg/palm per year) ^b	12–14	381	313	237	210
Mean leaf area (m ² /palm) ^c	12–14	348	368	348	332
Yield/leaf area (kg FFB/m ²)	12–14	0.86	0.62	0.43	0.34
DM production/leaf area (kg/m ²)	12–14	1.09	0.85	0.68	0.35
Bunch no. per palm per year	12–14	12.9	10.7	7.9	6.7
Sex ratio (% female)	11–12	–	46	36	–
Abortion rate (%)	11–12	–	10	16	–
Mean bunch weight (kg)	12–14	23.4	21.2	18.8	17.4

Data from Breure (1988a, b, and unpubl.) and Breure *et al.* (1990).

^aAssisted pollination in year 5, weevil pollination in years 14 and 15.

^bOil content of bunches multiplied by 2.1 to allow for extra energy content of oil.

^cAssuming 40 leaves per palm.

due to both a decreasing sex ratio and an increasing abortion rate. At 11–12 years, these data were only recorded for the intermediate densities: sex ratio was slightly lower than in young palms, and abortion rate much the same. The much lower bunch number was thus partly due to a lower rate of leaf and inflorescence production (data not shown; see Section 4.4.3).

9.3.2 Agricultural and economic optima

Optimal density can be defined in several ways. The optimum for current yield is that density giving the highest yield in a single year. However, this is of little interest, because the optimal density changes with age. Competition between palms is probably mainly for light (although perhaps occasionally also for water), so optimal density is dependent on leaf area and, at least in young palms, rachis length (Smith *et al.*, 1996). Oil palms start to yield some years before they are fully grown; production may start 2.5 years after field planting, while the palm crown does not reach its final size for up to 10 years, so during the first few years of production the optimal density is constantly changing. Choice of planting density is thus a compromise between maximising early yields, which demands a high density, and avoiding excessive interpalms competition at maturity, needing a low density.

After about 10 years from planting, leaf area stops increasing and canopy size stabilises. The optimum density ‘at maturity’ can then be estimated. This is relevant to decisions on thinning of mature stands, but the agronomist making a decision on planting density will want to take account of yields earlier than 10 years after planting. To an investor, the most useful definition of the optimum is that density which will give the maximum cumulative profit or discounted cash flow over the expected life of the planting. To calculate this, estimates of future palm oil prices and labour costs are needed. These are inevitably uncertain, and so agronomists have often preferred to estimate the density giving the maximum cumulative yield. The optimal economic density may differ from this for a number of reasons (Section 9.3.3.2), but studies in Malaysia showed that the economic optimum did not differ much from that giving maximum cumulative yield (Corley *et al.*, 1973a).

9.3.3 Triangular planting

Because the palm canopy is approximately hemispherical, and the palm does not grow irregularly to fill available space as does a dicotyledonous tree, planting from the

early days of the industry was on an equilateral triangular pattern.

9.3.3.1 Optimal density for current yield

Prevot and Duchesne (1955) studied planting density and pattern in the Ivory Coast, and drew conclusions which the oil palm industry has followed more or less ever since. They compared two triangular and three square plantings, and by fitting straight lines to yield per palm against density, they obtained quadratic curves for yield per hectare, and thus estimated optimal density, as follows. If:

$$Y_p = a - bD \quad (9.1)$$

where Y_p is yield per palm, D is palms per hectare, and a and b are constants, then yield per hectare, Y_a , is:

$$Y_a = Y_p \times D = aD - bD^2 \quad (9.2)$$

A quadratic curve may also be fitted directly to data for yield per hectare. Whichever method is chosen, differentiation of the quadratic curve, and setting the differential to zero, gives the point at which Y_a reaches a maximum; this is equal to $a/2b$ palms per hectare. Prevot and Duchesne (1955) described a ‘competition factor’ which allowed yield to be predicted at densities other than those tested. This was equivalent to the regression coefficient b in Equation 9.1; they expressed this in absolute terms, but it is probably more useful if given as a percentage of yield at ‘standard density’ (Corley *et al.*, 1973a).

Prevot and Duchesne (1955) assumed a linear relationship between yield per palm and density in Equation 9.1; their trial did not have a sufficient number of densities to establish this clearly, but they quoted other data in support. With the introduction of systematic, fan-design spacing trials (Bleasdale, 1967; Goh, 1977), which generally include a large number of different densities, the shape of density–response curves has become more clearly defined. Goh (1982) showed that yield per palm does not actually decrease linearly with density, but only appears to do so over a middle range of densities. This is illustrated in Fig. 9.1. A variety of equations other than quadratic curves can be fitted to data from plant density trials, some of which were discussed by Corley (1976f) and Goh (1982). Goh tried a number of models with both a conventional and a systematic spacing trial, and found that the equation of Holliday (1960) was most suitable:

$$1/Y_p = a + bD + cD^2 \quad (9.3)$$

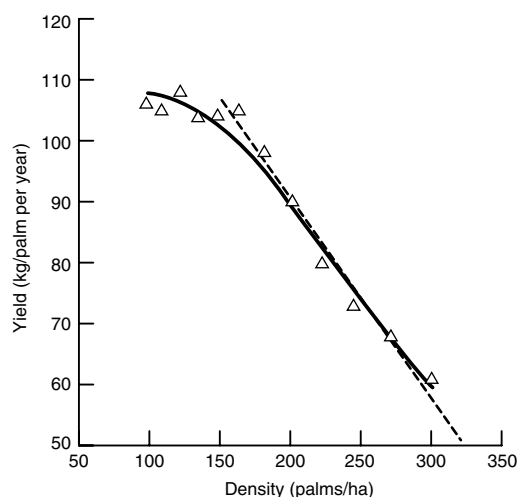


Fig. 9.1 Yield per palm, showing non-linear relationship with density at high densities, and little effect of density at low densities. The dotted line is a regression, fitted to densities between 164 and 300 palms/ha; the solid line is Holliday's equation (Holliday, 1960): $1/Y_p = a + bD + cD^2$. (Redrawn from Goh, 1982.)

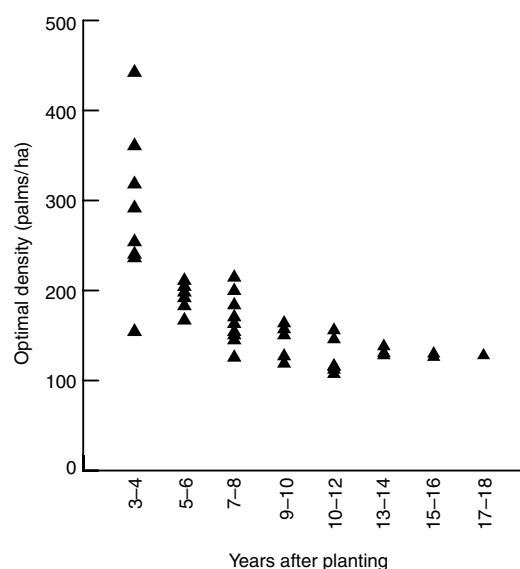


Fig. 9.2 Optimal density for current yield in Malaysia and Papua New Guinea. (Data from Ramachandran *et al.*, 1973; Breure, 2002; Corley *et al.*, 1973a; Donough and Kwan, 1991; Goh, 1982; Tan and Ng, 1977; B.G. Smith, unpubl.)

The optimal density derived by differentiation of this equation is $\sqrt{a/c}$ palms per hectare. As shown in Fig. 9.1, to some extent this equation allows for the relative constancy of yield at low density, as well as for curvature of the response curve at higher densities, but it does not give a perfect fit to the data. In practice, the choice of equation may not alter the conclusions much, although the optimum predicted by a quadratic curve (Equation 9.2) may be slightly higher than that from other equations.

Prevot and Duchesne (1955) found that the optimum for cumulative yield was around 140 palms/ha for both planting patterns (slightly higher for square), but square yielded about 5% less than triangular at the optimum. Based on this, 9 m or 30 ft triangular planting (143 or 138 palms/ha) became the industry standard. It may be noted that the two triangular densities in Prevot and Duchesne's trial were 117 and 176 palms/ha, neither of which is anywhere near the calculated optimum, so the almost universal acceptance of their conclusion is rather surprising. Vanderweyen (1952a) had recommended densities for Congo ranging from 135 to 180 palms/ha, depending on soil type and rainfall, with higher densities under poorer conditions. This approach is logical: optimal density probably depends mainly on leaf area and light interception (Smith *et al.*, 1996), and under poor conditions leaf area will be smaller, and hence the optimum density will be higher.

More recent work has confirmed that there are differences in optimal density between environments (Corley *et al.*, 1973a). There are also differences between types of planting material (Corley and Donough, 1992), as discussed in Section 9.3.5. Figure 9.2 shows optimal densities for current yield from several trials in Malaysia, and from one in PNG. Young palms are not much affected by competition before the leaves start to overlap, and yields per palm in the first few years may be more or less constant up to quite high densities. Thus, the optimum is very high when production starts, but falls to below 150 palms/ha within 10 years. At any one age, quite a wide range of optimal densities has been recorded. Corley *et al.* (1973a) showed that the optimum (D_{opt} , palms/ha) was more closely related to mean leaf area (LA, m^2) than to age, and they fitted the following curve to data from Malaysia and Nigeria (thus covering a wide range of absolute yield levels):

$$D_{opt} = 90.7 + 5538/LA^2 \quad (9.4)$$

In palms older than about 10 years, leaf area does not change much, so the optimum is expected to remain fairly constant (but it should be remembered that there may be errors or bias in the measurements of leaf area; see Section 4.1.3.1). However, Breure (1988b, 2002)

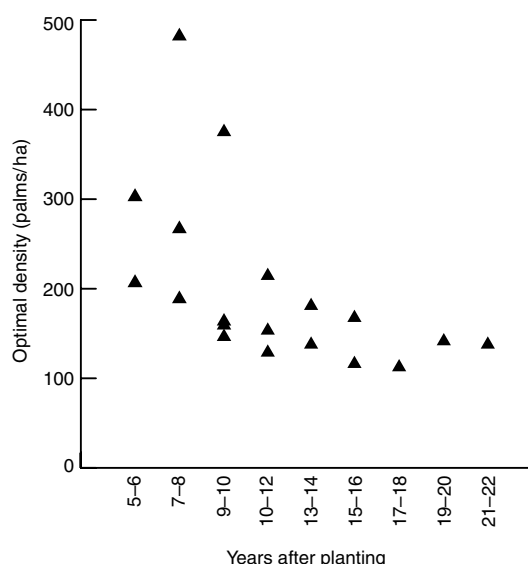


Fig. 9.3 Optimal density for current yield in African trials. (Data from Prevot and Duchesne, 1955; Sly and Chapas, 1963; IRHO, 1992c; Asamoah and Nuerthey, 1989; Inst. Agric. Forestry Res., Cameroon, unpubl. data.)

found that, after reaching a minimum at about 12–13 years after planting, the optimum density increased slightly in later years. This was attributed to better light distribution through the canopy as differences in palm height become more marked. This point is important when thinning is being considered (see below).

Figure 9.3 shows optimal densities for current yield in a few trials done in Africa. The optimum is generally higher than in the Far East at the same age. This reflects the slower rate of increase in leaf area in less favourable environments. A complicating factor is that closely planted palms may be better cared for than wider spaced palms, because of the greater proportion of weeded circles and shading of ground vegetation; as a result, in several trials the widest spacings have yielded less per palm in the early years than closer spacing (e.g. Sly and Chapas, 1963; Corley, 1973b).

9.3.3.2 Optimal density for cumulative yield or profit

As pointed out earlier, the optimal density for current yield is less important than that for cumulative yield, or for cumulative profit or discounted cash flow (DCF). To calculate this for the life of a planting, one needs to know what yields will be up to the point of replanting.

Yields for the latter part of this period must be estimated by extrapolation; direct recording would make the duration of an experiment unacceptably long, and the conclusions might only be valid for planting material and management techniques current 25 years earlier. What has usually been done is to assume that the yields at 10–12 years after planting will be representative for the rest of the life of the planting. Redshaw and Siggs (1995) included an age-related decline of 0.38 t FFB/ha for each year, and a further decline attributable to a loss of palms with age of 0.09 t/ha for each palm lost. There are two problems with this extrapolation. First, any experimental error in the data for the last years actually recorded is amplified in estimating cumulative yield. This is not too important for financial calculations, because profits in the later years of the planting will be heavily discounted. Secondly, yields in those years may not be representative of later years, if Breure's contention (1988b), that optimal density for current yield increases again after 12 years, is correct.

Corley *et al.* (1973a) calculated cumulative yields for 25 and 30 years for densities varying from about 143 to 180 palms/ha. They found that optimum densities varied from 150 to 170 palms/ha, and that the better the growing conditions the lower the optimum within these limits. They concluded that about 158 palms/ha was a good general compromise, but suggested 150 palms/ha for good coastal soils in Malaysia, 158 palms/ha for good inland soils and 165 palms/ha for poorer soils, using planting material current at that time, and with adequate fertiliser.

The optimal economic density differs from that for cumulative yield for two main reasons. First, establishment and early maintenance costs increase linearly with increasing density; yield per hectare does not increase linearly, but reaches a plateau around the optimal density, so a small decrease in density below the optimum for yield will give a greater saving in costs than the value of the crop lost. Thus, Surre (1955) concluded that the optimal economic density would always be lower than that for yield. However, when a DCF method is used, yield in the early years will be assigned a greater value than that in later years. Since the optimal density for yield is higher in the early years, this will give an economic optimum above that for cumulative yield. As a result of these two opposing factors, the economic optimum may be either above or below that for cumulative yield; this can be seen in the results given by Corley *et al.* (1973a). When the value of the annual crop is low, whether as a result of low oil price or of low yield, establishment costs will be relatively important, and the economic optimum will be low. In

contrast, the higher the discount rate, the greater the relative value of the early years and the higher the optimum. Overall, Corley *et al.* (1973a) found that the economic optimum was not very different from the optimum for cumulative yield.

Other factors may affect the economic optimal density to some extent. Mean bunch weight and bunch number per palm decrease as density increases, and this may lead to higher harvesting costs at higher density. As density increases, palm height increases, thus tending to increase the cost of harvesting, and perhaps to shorten the economic life of the planting. This effect is quite small, however: Sly and Chapas (1963) showed that the extra height increment caused by an increase in density of 1 palm/ha was about 0.06 cm/year in Nigeria, while Corley (1976f) estimated 0.11 cm in Malaysia. Thus, a change in density from 140 to 160 palms/ha might lead to an increase in height after 30 years of up to 66 cm, equivalent to a reduction in the economic life of the planting of only about 1 year. Redshaw and Siggs (1995) also estimated a difference of 1 year for these densities.

A final point to note is that it is now clearly established that fruit set, and hence oil/bunch and kernel/bunch, tends to increase with planting density (Breure *et al.*, 1990; Donough and Kwan, 1991; Rao *et al.*, 1992). Thus, the optimum for oil yield will be slightly higher than that for yield of fruit. Earlier work, indicating no such trend, was done before the introduction of the pollinating weevil to South-east Asia (Corley, 1976f; see also Table 9.1).

9.3.3.3 Conclusions

The optimal densities estimated in several different studies are shown in Table 9.2. With the exception of Nigeria (where both papers refer to the same trial, but including different age ranges), the range of optima is quite small. Note that Ramachandran *et al.* (1973) only started recording at 7 years, so they will have underestimated the optimum for total yield. Corley *et al.* (1973a) found that the curves of cumulative yield plotted against density were quite flat-topped, and they estimated that a deviation of 10 palms/ha on either side of the optimum would not reduce cumulative yield by more than 1%. Redshaw and Siggs (1995) found little difference in DCF return between 128, 143 and 160 palms/ha in North Sumatra. Based on these observations, and on Table 9.2, a density of about 150 palms/ha should be a reasonable compromise for most environments in Malaysia and Indonesia. A higher density may be needed in parts of West Africa, and a lower density may be optimal on volcanic soils in PNG.

Table 9.2 Optimal densities for cumulative yield or profitability.

Environment	Optimum for	Optimum (palms/ha)	Ref.
Ivory Coast	Yield to 21 years	139	1
Ivory Coast	Economic return	125	2
Nigeria	Yield to 16 years	228	3
Nigeria	Yield to 27 years	171	4
Malaysia, coastal	Yield	153	5
Malaysia, coastal	Yield, 25 years	156	6
Malaysia, coastal	DCF return	151	6
Malaysia, good inland	Yield, 25 years	162	6
Malaysia, good inland	DCF return	158	6
Malaysia, poor inland	Yield, 25 years	169	6
Malaysia, poor inland	DCF return	166	6
Malaysia, inland	Yield, years 7–19	130 ^a	7
Malaysia, inland	Yield	141	8
Papua New Guinea	Yield, 14 years	119	9

^aEarly years excluded, so true optimum for cumulative yield will be higher than that shown.

DCF: discounted cash flow.

References: 1: Prevot and Duchesne (1955); 2: Surre (1955); 3: Sly and Chapas (1963); 4: Malipant (1978); 5: Tan and Ng (1977); 6: Corley *et al.* (1973a); 7: Ramachandran *et al.* (1973); 8: Goh (1982); 9: C.J. Breure (unpubl.).

9.3.4 Planting patterns other than triangular

Prevot and Duchesne (1955) concluded that square planting gave lower yields than triangular planting. Subsequent work generally supports this conclusion. Sly and Chapas (1963) in Nigeria compared four triangular densities, and also a range of non-triangular patterns. Large departures from triangularity decreased yields per palm greatly: 30 ft triangular (9.1 m) yielded twice as much, over 12 years, as 65 × 12 ft (19 × 3.7 m), although both have 138 palms/ha. Corley (1973b) found that yields were about 7% lower from an 'open hexagon' planting than from a triangular planting at the same density. Guldentops and Scuvie (1968) compared a range of planting patterns; none of their plantings was exactly triangular, but the nearest to triangular gave the best yields. The only contrary result came from Nawi che Yusoff *et al.* (1984), in an oil palm–cocoa intercropping trial. These authors found that 143 palms/ha gave the same yield, whether planted at 9 m triangular or at 10 × 7 m rectangular (the latter intercropped with cocoa). This result may be related to the additional fertiliser supplied to the cocoa.

While the superiority of triangular over other arrangements is clearly established, there are some

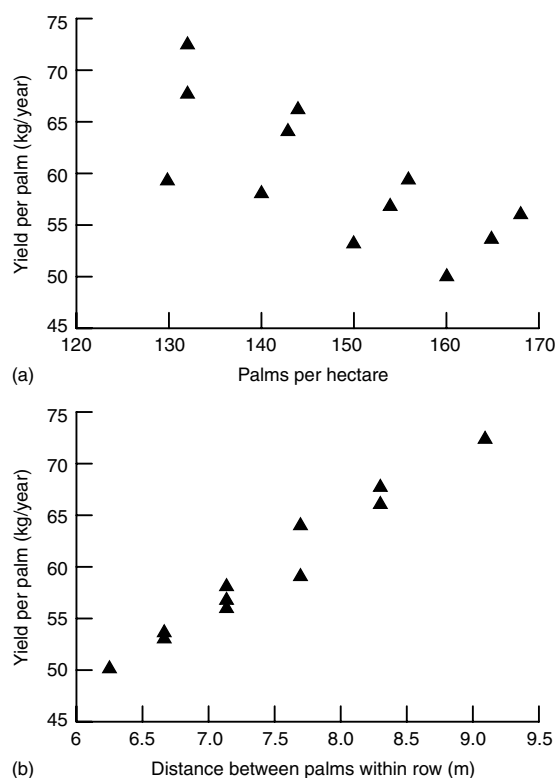


Fig. 9.4 Yield per palm, from a range of rectangular plantings, plotted against (a) planting density, or (b) distance between palms within rows. (From Guldentops and Scuvie, 1968.)

circumstances, such as mixed planting or intercropping with food crops, in which avenues of palms might be adopted. Guldentops and Scuvie (1968) found that, if density was varied by changing the distance between palms within the row, while distance between rows was constant, yield was better correlated with the distance between palms (Fig. 9.4b) than with density per hectare (Fig. 9.4a). From this, we may conclude that, if an avenue pattern is to be adopted, the spacing within the rows should not be reduced in order to try to maintain total number of palms per hectare. Guldentops and Scuvie's plantings were all in double rows, with only 6 m between the rows in each pair. If close spacing is adopted, though, single rows will be preferable to paired rows, as each palm will then have only two close neighbours instead of four. Nawi che Yusoff *et al.* (1984) found that double rows at 7 m triangular, with a 20 m interrow, gave yields 24% lower than single rows at 7×13 m, although the density is much the same.

9.3.5 Progeny differences

The majority of trials, and thus the general conclusions drawn so far, relate to mixed commercial planting material. Where trials have been done with individual progenies, variation in optimal density is apparent. The first data suggesting progeny differences came from Nigeria. In the experiment described by Sly and Chapas (1963), each replicate was planted with a different progeny; this precluded statistical analysis of progeny differences, but the differences were so striking that there was little doubt that they were real. Table 9.3 shows the yield in the 12th bearing year, the height and the optimal density (calculated from Equation 9.2) of six selfed *dura* progenies at four different triangular spacings. It will be noted that in the majority of progenies the yield by this age was low at the highest density, but two progenies gave higher yields at 199 than at 138 palms/ha, and both had calculated optima (for current yield) above 200 palms/ha. The height of these two progenies was relatively little affected by density (progeny 103.149 was also little affected, but did not have a high optimal density).

Corley and Donough (1992) showed statistically significant differences between clones in optimal density, with a range, at 5–8 years after planting, from 156 to 260 palms/ha. Smith *et al.* (1996) showed that in the early years of production, optimal density was related to rachis length: palms with short rachises compete with each other less, at any density, than those with longer rachises, and so have a higher optimal density. Later, when leaves of all palms were overlapping, the optimum was more related to leaf area: palms with small leaf area must be more densely planted to achieve the optimum leaf area index.

One objective of breeding has been to identify progenies that maintain a high yield per palm at high density (see Section 5.4.4). Breure and Corley (1983) showed that palms having a high bunch index (ratio of bunch dry matter to total dry matter) in the early years, before interpalms competition became too severe, yielded better in later years, at both standard and higher densities, than palms selected for other growth parameters, including bunch yield itself.

9.3.6 Thinning

Because the optimal density is high in the early years, and lower later, the possibility of planting at a high density and then thinning has often been considered. Thinning is also sometimes recommended for plantings that were not originally intended to be thinned,

Table 9.3 Effect of spacing on selfed *dura* progenies.

Mean height, and fruit bunch yield per hectare in the 12th year of bearing, height difference between highest and lowest densities, and optimal density from Equation 9.2; the density giving the greatest yield for each progeny is shown in bold type.

Parent	Density (palms/ha)								Height diff. 282–70 (m)	Optimal density (palms/ha)
	282		199		138		70			
	Height (m)	Yield (t/ha)	Height (m)	Yield (t/ha)	Height (m)	Yield (t/ha)	Height (m)	Yield (t/ha)		
103.149	4.97	7.68	4.42	12.27	4.30	13.33	4.45	10.70	0.52	158
103.90	5.79	7.26	4.33	10.21	3.99	12.12	3.99	9.68	1.80	158
103.426	4.24	11.30	4.05	12.16	3.38	8.02	3.32	6.12	0.92	240
103.114	6.95	6.45	5.49	8.81	5.27	11.06	4.48	10.37	2.47	150
551.256	6.58	6.08	5.82	9.95	6.40	13.30	4.94	10.02	1.64	153
103.151	4.21	8.34	4.33	9.74	3.50	9.33	4.02	5.33	0.19	208

From Sly and Chapas (1963).

but in which vegetative growth has been more vigorous than expected. A distinction may be made between deliberate high-density planting, intended to be followed by thinning, and thinning of mature stands planted at 'normal' density. Natural thinning may also occur, as a result of disease, but may tend to be clumped, rather than regular.

9.3.6.1 Natural thinning

Natural thinning as a result of disease occurs in most environments; in Africa, *Fusarium* wilt is the most likely cause; in Malaysia, *Ganoderma*, and in Latin America fatal yellowing. These diseases are all discussed in Chapter 12. Nazeeb *et al.* (2000) suggested deliberately planting at a higher density than normal where disease losses are expected to be severe. They showed that planting at 170 palms/ha did not cause any increase in *Ganoderma* incidence compared with 136 palms/ha, and gave a consistently higher yield up to the seventh year of production.

Comparisons of yields before and after disease losses have been quoted in support of deliberate thinning policies, but such data are not very reliable. Apart from the difficulty of making statistically valid comparisons between years and fields, there is also the fact that infected palms may be yielding poorly for some time before they die, so that their removal may make no apparent difference. Prendergast (1957) noted that up to 20% losses from *Fusarium* wilt might have little effect on yield, but other studies have indicated yield loss (see Chapter 12).

Dumortier *et al.* (1992) developed a correction factor for yields of individual palms with missing neighbours.

Based on several sets of data (Bachy, 1965; Corley, unpubl.), it appeared that each missing palm increased the yield of its neighbours by about 11%, for mature palms at normal densities. This factor was used to adjust yield data in a selection programme, in an area where wilt losses were high. Note that, if one palm in seven is removed, as in Fig. 9.5a, the yield of the remaining six palms will be less ($6 \times 111\% = 666$) than the yield of the original seven ($7 \times 100\% = 700$). This implies that deliberate thinning is unlikely to be useful at normal planting densities, unless only low-yielding palms are removed.

9.3.6.2 Thinning of mature stands

This subject was reviewed in some detail by Corley (1977a). He listed symptoms that are sometimes taken as indicating a need for thinning, and pointed out that most of these were subjective and would not be reliable indicators. Corley also noted that there was only a limited number of ways in which a palm stand could be thinned systematically. Each palm has six neighbours, so it is possible to remove one neighbour from each palm, two neighbours, and so on. The resulting thinning patterns involve removal of 14, 25, 33 or 50% of palms (Fig. 9.5). Menendez (1988) pointed out that there are two ways in which 33% thinning can be done: one removes three neighbours from every palm, while the other removes only two neighbours. He compared the two methods in one experiment; as expected on theoretical grounds, the former gave the higher yield.

Menendez (1988) obtained a cumulative yield increase of 7% over 6.5 years in West New Britain after thinning a stand of 143 palms/ha by 33%, 7 years after

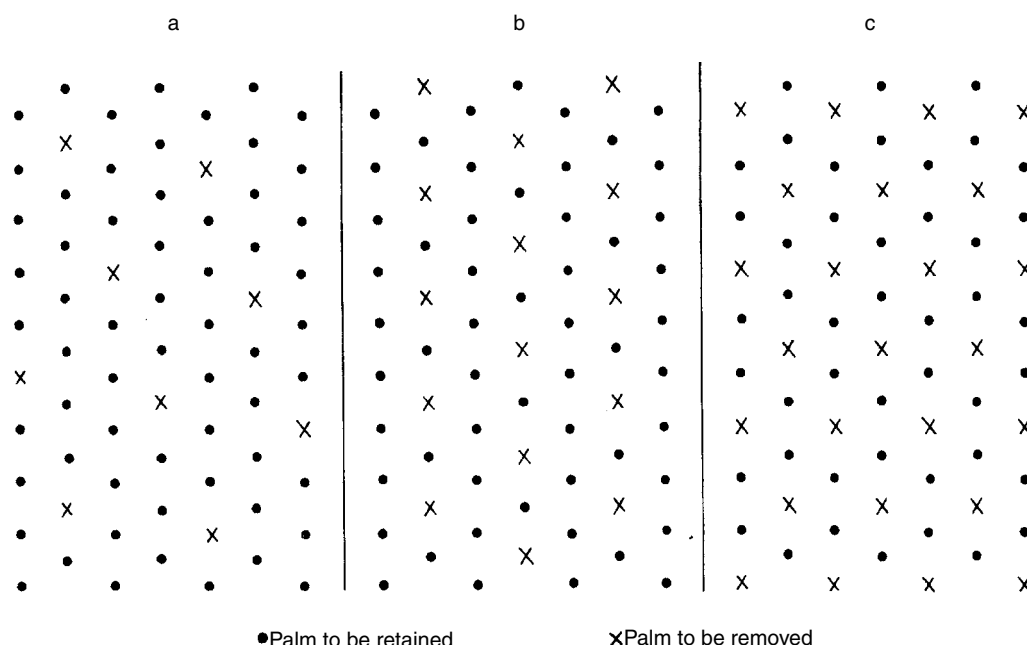


Fig. 9.5 Possible thinning patterns, removing (a) one, (b) two, or (c) three neighbours from every palm. (From Corley, 1997a.)

planting. In another experiment, though, thinning by 14%, 9 years after planting gave a 7% yield loss over 4.5 years. The yield differences in these trials were not statistically significant.

Nazeeb *et al.* (1990) gave results from two thinning trials on inland soils in Malaysia. In one, with 16-year-old palms at 165/ha, 14% thinning gave a yield increase of nearly 5% over the next 5 years, and an increase in net present value (discounting at 8%) of 8%. Weeding costs were increased, but fertiliser costs were reduced proportionate to the palms removed. Thinning by 25% left yield unchanged, while 33% reduced yield by 7%. In a second trial, with 15-year-old palms at 148/ha, all thinning treatments reduced yield over the next 5 years, by at least 9%.

In neither of these studies were oil yields measured; it is known that oil/bunch tends to increase slightly with increasing density (Donough and Kwan, 1991), so it may be assumed that thinning will reduce it slightly. Taking this into account, and considering all the trials, a yield loss appears rather more likely after thinning than a gain.

Commercially, thinning is usually considered at about 10–12 years after planting, when leaf area and interpalms competition reach a maximum. However, Breure (1988b, 2002) found that, after reaching a maximum at about 12–13 years after planting, light interception diminished

again. Thus, there could be a transient period during which thinning would be beneficial, but within a few years the need for it may disappear.

The general conclusion must be that thinning of stands at normal density is not very likely to be profitable. Turner and Gillbanks (1974) recommended poisoning and felling unproductive palms, including sterile palms and those giving male flowers only. Palms much smaller than their neighbours, and yielding very little (often a result of replacement long after planting), can also be removed.

9.3.6.3 Variable density and planned thinning

Given the changes with age in optimal density for current yield, the attraction of initial high-density planting followed by thinning is obvious. The aim is to take advantage of high early yields from high density, and then to thin when interpalms competition starts to limit yield. Figure 9.6 shows some hypothetical yield curves. The hope is that thinning can be done at such a time and in such a way that the loss of crop after thinning is less than the early yield gain.

Corley *et al.* (1973a) looked at several thinning options in Malaysian trials. Several ways of interplanting additional palms were tested, the aim being to leave

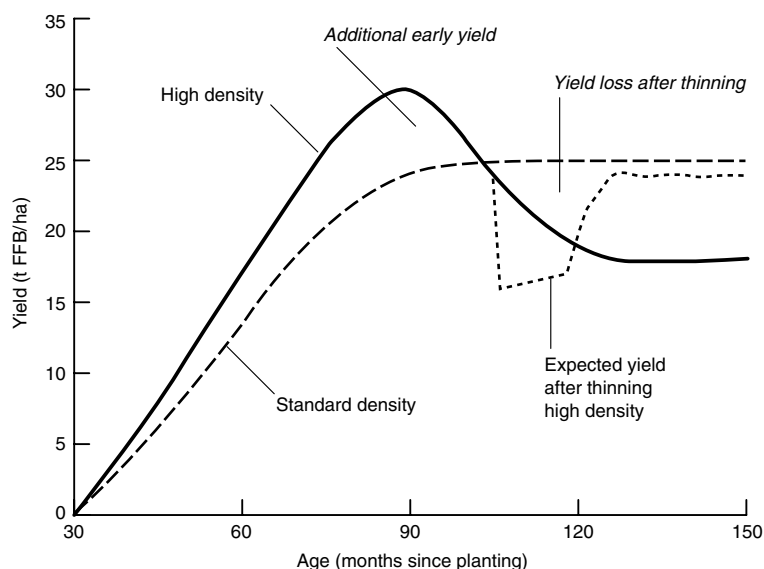


Fig. 9.6 Hypothetical yield curves at standard and high density. For high density planting and thinning to be profitable, the additional early yield must be sufficiently greater than the yield loss after thinning to compensate for the extra costs of high-density planting.

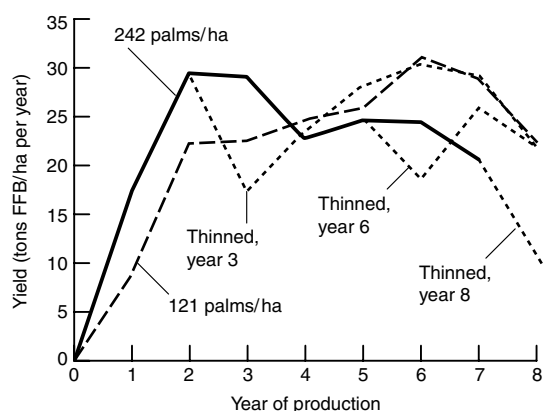


Fig. 9.7 Response to thinning from 242 to 121 palms/ha. Three thinning treatments were tested: thinning at the start of the third, the sixth or the eighth year of production. Dotted lines show yields after thinning in each case; the solid line shows the mean yield of remaining high-density plots. (Redrawn from Corley *et al.*, 1973a.)

- By the fourth year, yields per hectare at the high density had started to fall below those at the low density. Delaying thinning beyond this point therefore simply results in additional crop loss.
- Thinning after the fourth year was not tested, but where thinning was done after the fifth year, it took 3 years for the thinned stand to recover to the same yield level as the low-density control plots.
- When thinning was done after the second year, recovery was faster, but the additional crop harvested before thinning was hardly greater than the loss after thinning.

a regular triangular planting after thinning, at or close to the optimal density at maturity. Corley *et al.* pointed out that thinning must be at, or before, the time when yields per hectare from the normal and high density plantings are equal, and they showed that leaf area measurements could be used to predict this time. Results of a thinning trial are shown in Fig. 9.7, from which several points may be noted.

Even in the 1970s, therefore, when management of immature palms was not as intensive as now, and hence growth was slower, Corley *et al.* (1973a) concluded that, to avoid a yield loss, thinning was needed before any real benefit had been gained from the extra palms.

Nazeeb *et al.* (1990) suggested an alternative approach: planting in a triangular pattern, with thinning to leave a non-triangular stand. This has the advantage that thinning can take place later; because competition seems to depend more on the nearest neighbour than on the average distance of all neighbours (Guldentops and Scuvie, 1968), a triangular stand will suffer less interpalm competition than any other pattern at the same density. Several trials have been planted to investigate the optimal time and intensity of thinning, but at the time of writing none had reached an age at which conclusions could be drawn. It is worth

Table 9.4 Labour requirements for establishing palms

	Source of data						
	1	2	3	4	5	6	7
Manual operations (man-days/ha)							
Lining	11	3	4	10	3	1	7
Transporting seedlings	1–3	2	–	–	–	2	–
Digging holes, planting	4–10	7	14–22	21	6	4	22
Rodent control	1	–	–	3	–	0.1	–
Total	17–25	12	18–26	34	>9	7	29
Mechanised operations (tractor hours/ha)							
Transporting seedlings	0.5–1.5	–	–	–	–	1–1.5	–

Sources: 1: Jacquemard (1998); 2: Ghana (data courtesy of Benso Oil Palm Plantation, 2000); 3: Congo (Vanderweyen, 1952a); 4: Nigeria (Hartley, 1988); 5: North Sumatra (data courtesy of London Sumatra Indonesia, 2000); 6: Malaysia (Bevan and Gray, 1969); 7: Indonesia (Hakim *et al.*, 1998).

noting that the intensity of thinning is more critical than the time. If thinning is done at the wrong time, there may be additional yield loss for a few years, but if the wrong intensity is adopted, any loss will persist for the remaining life of the planting, as one thinning pattern cannot be converted into another.

9.4 PRACTICAL ASPECTS OF FIELD ESTABLISHMENT

9.4.1 Lining

Methods of marking out planting points are discussed in Chapter 8. For equilateral triangular plantings, the relationship between planting distance (x , m) and density (D , palms/ha) is given by:

$$D = 10,000/0.867x^2 \quad (9.5)$$

The required planting distance for any given density can be calculated from:

$$x = \sqrt{10,000/0.867 D} \quad (9.6)$$

For non-equilateral plantings, where x_1 = distance between palms within row, and x_2 = distance between rows (perpendicular to rows, not distance between palms in adjacent rows):

$$D = 10,000/(x_1 x_2) \quad (9.7)$$

9.4.2 Costs

Costs, in man-days/ha, are given in Table 9.4 for the main operations involved in planting (land preparation costs are covered in Chapter 8). There are some inconsistencies in the figures. The requirements for lining given by Jacquemard (1998) and by Hartley (1988) for Nigeria are surprisingly high, compared with others. The Nigerian and Congo figures for holing and planting include transport from the nursery, and lifting of plants from the field nursery. The last is an additional cost, no longer applicable with polybag nurseries.

Azmi Yahya and El Pebrian (2001) described a mechanised oil palm planter which digs a planting hole, places the seedling in the hole, and fills and compacts the soil. Labour requirement was less than half that for manual planting, and costs, including depreciation, were slightly lower. Costs of applying EFB mulch, in circles around the young palms, were given by Lim K.N. *et al.* (1995). Hornus and Nguimjeu (1992) and Gurmit *et al.* (1981) gave detailed costs for spreading EFB between mature palms. Hakim *et al.* (1998) compared costs for underplanting and conventional replanting in Indonesia. Underplanting was appreciably cheaper, but this was partly because items such as cover crop establishment, which may be desirable, were excluded.

Chapter 10

Care and Maintenance of Oil Palms

10.1 CARE OF PALMS AND PLANT COVER

10.1.1 Value and function of covers

Plantation crops of tree size need another storey of vegetation, at ground level. At one time rubber planters believed that the surface soil should be absolutely bare, but found that this caused soil damage. Soil cover is necessary for five main reasons. First, the soil surface needs protection from erosion by raindrops or running water (see Sections 8.1.3.6 and 11.7.4.1). With tall palms, the impact of drops falling from the fronds can be equal to that of heavy natural raindrops that have reached their terminal velocity, and this can easily break up a bare soil surface and disperse the finer material. The intensity of rainfall in the humid tropics is such that the infiltration capacity of the soil can easily be exceeded, so that water runs over the surface and fine soil dispersed in the water will block the pores. Secondly, it costs more to keep the soil surface free of plants than to accept a surface cover of plants. Thirdly, there are various advantages that such plants can bring, such as nitrogen fixation by legumes, and improvement of soil structure and infiltration rate, that reduces runoff. Fourthly, the soil temperature is moderated, and fifthly, there is less *Oryctes* beetle damage with young palms, and the possibility of biocontrol of some insects.

As against these important advantages, the main disadvantage is that the cover plants may compete against the tree crop for nutrients and water, especially at the seedling stage. This must be considered where a cover plant is very vigorous, very tall or growing very close to young palms. In two experiments in West Africa the ring weeding and clearing of the harvesting paths was maintained, but the rest of the cover was allowed to grow with only a single annual cutting, rather than the six that would have been normal, to keep it down to around 30 cm height. The effects of competition can be seen in Table 10.1 (Hartley, 1988) (see Section 8.4.3.1). However, the proof of interplant competition requires a field experiment, and competition has often been assumed to exist on rather slight evidence.

Table 10.1 Yields of plots slashed annually, compared with plots receiving normal maintenance, as %

	Forest area	Previously cultivated area
<i>First 8 years of bearing</i>		
Normal maintenance	100.0	100.0
Annual slashing only	79.4	69.1
<i>Later bearing years</i>	(11 years)	(2 years)
Normal maintenance	100.0	100.0
Annual slashing only	102.0	85.4

After Hartley (1988).

The general considerations in operating a plant cover are (Hartley, 1988, p. 420):

- to prevent competition between the palms and the cover plants, by ring weeding and cover control
- to cover the ground rapidly in the plantations early years, and prevent erosion and runoff, while requiring low maintenance
- to maintain a cover under palms, especially young palms, that will discourage harmful weeds, while remaining easy to control
- to maintain fertility and, if possible, add to it.

A very large part of the management of young palms after their planting (see Chapter 9) is concerned with cover management.

10.1.2 Maintenance of young plantations

10.1.2.1 Management of young palms

The fertilising of young palms is considered in Chapter 11. The seedlings must be kept free of competing vegetation at all times by clearing a circle around each palm, initially around 1 m radius, but increasing with the size of the palm. It is preferable not to use herbicides while the plant is small. Access paths are installed, at first quite sparingly, but soon increased to one path every two rows; these become the standard harvesting and access paths. Spot-weeding of deleterious weeds such as

Mikania continues, manually or with herbicides. The details of these procedures are given in Rankine and Fairhurst (1998b). Ablation and the initiation of harvesting are described in Section 10.2.2.

10.1.2.2 Establishment and maintenance of natural cover

The simplest form of such cover is to allow plants to spring up naturally, and then control them by periodic slashing, mowing grazing (8.4.3.4) or the use of herbicides, and by formation of close-weeded circles and pathways. If the plantation is opened from forest it will at first be largely forest species, from seeds, stumps or roots, as the propagules left over in the soil from largely woody vegetation. At planting time Ismael *et al.* (1995) found 25 identified seed species in an oil palm plantation opened up from forest, with 3362 seeds/m². These numbers declined sharply with the age of the plantation. If the plantation is a replant, the natural vegetation will contain far more pioneer species, which come in with the decreased competition following the removal of old palms, because of the small number of species present at the time of felling. If a plantation is started on either forest, grassland oralang areas, the existing seed burden will be very different, although the plant population will gradually change to the one that is most competitive under those conditions.

In West Africa forest regrowth can be very rapid after felling and planting, especially at the beginning and the end of the rainy season, and up to six slashings may be required in a year (Hartley, 1988) (Table 10.1). The great importance of keeping the natural cover under control is obvious, both where the area was previously under forest

or under cultivation. Later, when the palms were over 8 years old, the competitive effect remained strong on previously cultivated soil but not on the forested soil, presumably because the latter was more fertile. It must be accepted that all covers are to some degree competitive with young palms, because when the soil was tilled regularly during bearing, the yields were initially much higher than with natural cover (Table 10.2). The establishment of a legume cover (usually *Pueraria phaseoloides*) is in part aimed at reducing the labour requirement, although the legume itself also grows vigorously under these conditions and requires frequent cutting back (Plates 10.1, 10.2).

In the Asian conditions regrowth of natural vegetation may be less rapid. The less competitive, and hence more desirable species, such as the fern *Nephrolepis biserrata*, shrubs from stumps after a non-burn clearing, or herbaceous weeds and grass after burning, all grow slowly and with legumes form the main cover in adult plantations (Plate IIIA). The aim has been more towards weeding out undesirable species rather than cutting back all the vegetation. Only four species are generally accepted as being damaging weeds in Asia,

Table 10.2 Yields of palm plots given regular tillage after opening by burning, compared with plots given normal slashing maintenance of natural cover, as %

	First 3 years	4th–7th years	8th–11th years
Burning, normal maintenance	100	100	100
Burning, regular tillage	277	92	82

After Hartley (1988).



Plate 10.1 A *Pueraria phaseoloides* cover still in almost pure stand between 7-year-old palms at the Oil Palm Research Centre, Kusi, Ghana, with good ring-weeding.



Plate 10.2 A good mixed *Pueraria* and natural cover in a 'closed in' field in Nigeria.

Table 10.3 Yields (t FFB/treatment) from palms with different types of managed interrow vegetation

Treatment	Grass	<i>Mikania</i>	<i>Nephrolepis</i>	<i>Pueraria</i> + <i>Centrosema</i>	<i>Flemingia</i>	<i>Pueraria</i> + <i>Flemingia</i> + <i>Centrosema</i>
No fertiliser	9.18	7.79	8.54	9.74	9.18	9.31
With fertiliser	9.17	8.81	9.66	9.92	9.53	9.64
Mean	9.17	8.30	9.10	9.83	9.36	9.47

After Turner and Gillbanks (1974).

Ischaemum muticum, *Imperata cylindrica*, *Mikania cordata* and possibly *Asystasia gangetica* (Quah *et al.*, 1999), and these should be rigorously removed from any cover in which they are found, although other species may also be undesirable (Turner and Gillbanks, 1974) (Table 10.3). The precise mechanism whereby weeds damage crop plants is not known, but is usually assumed to be due to direct competition for light, water and/or nutrients. The possibility of more complex mechanisms must be borne in mind (Tinker and Nye, 2000, p. 247). Thus, *Chromolaena odorata*, which is a widespread weed in the humid tropics of Africa and Asia, has been shown to have allelopathic effects by the production of phenolic and other compounds from the leaves and other plant parts (Ambika, 2002).

The effect of fertiliser in relation to plant cover is interesting, as it had no effect on palms with a grass cover and very little with a legume cover. However, it greatly increased the yields with both *Nephrolepis* and *Mikania*, although neither reached the yield level with legume cover and fertiliser. It is likely that the effect in

Table 10.4 Effects of nitrogen and of different covers, including legumes, on yields in first 3 years of oil palm bearing

N rates	FFB yields (t/ha per year)			
	Legumes	Naturals with legumes	Naturals with <i>Mikania</i>	<i>Mikania</i>
N0	15.5	15.8	14.6	12.8
N1	14.9	16.0	13.8	13.8
N2	15.9	16.4	16.4	14.9

After Teoh and Chew (1980).

this case is due to competition for soil nutrients, as is shown clearly in Table 10.4 (Teoh and Chew, 1980). The progressive increase in the response to nitrogen from legumes, through naturals with legumes, naturals with *Mikania* to *Mikania* alone emphasises the benefits of legumes, and the ability of *Mikania* to compete

for nitrogen. In West Africa and South-east Asia *Chromolaena* (formerly *Eupatorium*) is also a serious weed, and if it dries out during the dry season it becomes a fire hazard.

In America grass species are the normal natural vegetation cover in areas where ranching is common, and these can be very competitive because of their size (e.g. *Hyparrhenia rufa*, *Panicum maximum* and *Pennisetum purpureum*). Where the plantation is opened from forest and ranching is not common in the area, grass seeds may not be ubiquitous and *Pueraria* can easily be established, but even here grasses will probably enter later. These must be kept under control by spot-spraying. *Brachiaria* is used as pasture grass in Colombia, but is believed to be highly competitive to palms. If wetland rice can be grown on an area once or twice before draining and planting palms, this is an excellent way of eliminating grasses.

10.1.2.3 Establishment and maintenance of legume covers

There has been a continuing argument about the use of natural covers or of planted covers (usually creeping legumes), with widely varying attitudes of planters to cover management (Hartley, 1988, p. 418, Section 8.4.2). Broughton (1976) showed very clearly in a review of published experiments in Malaysia that palm fields with legume covers almost always outyielded those with natural cover and responded more to fertilisers. Legume covers grew well at first, and as the palm canopies started to meet, they died back, thus releasing very significant quantities of nutrients to the soil. *Pueraria* and similar legumes give an even cover, are fairly easily maintained, have a root system that is not especially competitive, do not show intense competition with palms, are low growing and improve soil fertility (Turner and Gillbanks, 1974). Rankine and Fairhurst (1998b) gave a slightly different list of advantages, including pest control in discouraging rhinoceros beetle from breeding in felled palms, as did Hartley (1988, p. 434). It is difficult to visualise alternative cover plants that can show much improvement on these factors (Table 10.3) (Turner and Gillbanks, 1974). Many have been proposed in the past (Hartley, 1988), but all have eventually been found to be less satisfactory than the standard legume cover plants.

Hartley (1988) felt that a reconsideration of the benefits of legumes was at that time in process. In fact, the use of legume covers is now universal, and has remained so during the change from burning to zero-burning during establishment of plantations (see Section 8.4.2), the only drawback being that the labour shortage in Malaysia may prevent legume seed being sown at the right time. Jaquemard (1998) simply took it for granted that legume

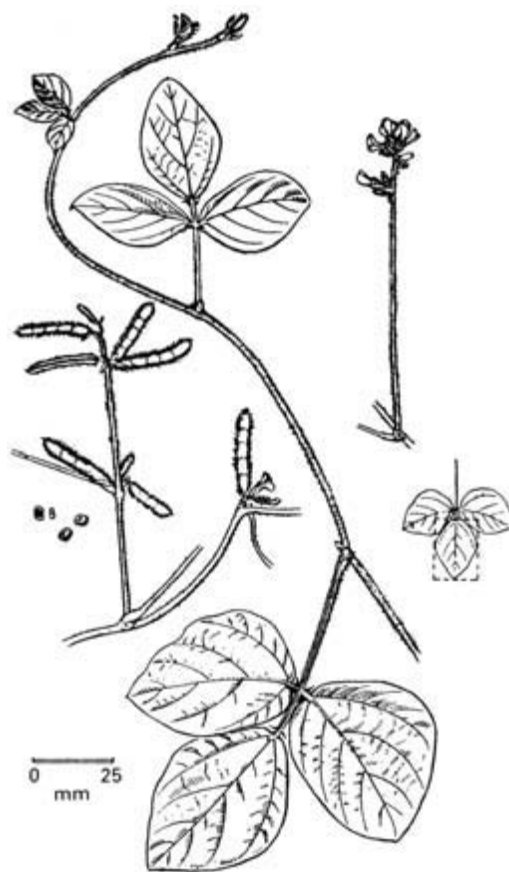


Fig. 10.1 Drawing of *Calapogonium mucunoides*. (After Hartley, 1988.)

covers would be used, mentioning *Pueraria phaseoloides*, *Mucuna cochinchinensis*, *Centrosema pubescens*, *Calapogonium mucunoides* and *Calapogonium caeruleum* as being sown before palm planting, and this is certainly true in the Asian plantations (Plate IIIB). Rankine and Fairhurst (1998b) took a similar view, and included in their list *M. cochinchinensis* and *C. caeruleum*. Of these legumes, *P. phaseoloides*, *C. mucunoides* and *C. pubescens* can be used in a mixture very effectively, because of their different growth patterns. *Centrosema pubescens* is not very competitive, *Mucuna* grows rapidly but also dies back quickly, and *C. caeruleum* is good under shade, but has poor viability (Figs 10.1 and 10.2). Hartley (1988) also mentioned *Dolichos hosei* and various non-legumes, but these do not seem to have gained much support and are probably now irrelevant. There may be a need for seed pretreatment, or for the use of *Rhizobium* inoculum if they are being sown into an area that has not carried such legumes before (Hartley, 1988). Rankine and



Fig. 10.2 Drawing of *Pueraria phaseoloides*. (After Hartley, 1988.)

Fairhurst (1998b) give directions for physical scarification of the seed surface, and for the preparation of the *Rhizobium* inoculant. Establishment is usually very easy in Africa, but there may be more problems in Asia, although establishment on volcanic soils is usually very good. The reasons for such failures have been given as lack of soil fertility, *Rhizoctonia* and other fungi, aphids, beetles, caterpillars, slugs and snails, and the soil nematode *Meloidogyne javanica* (Hartley, 1988). This range of pests rarely prevents any legumes becoming successfully established. It is normal in Asian plantations to give an insurance dressing of rock phosphate to the covers during the first year after sowing. Hartley (1988) suggested that four dressings be given during this first year, but the slow reaction of rock phosphate probably means that most of it could be given as one dressing at the time of sowing.

In Malaysia an experiment on rubber suggested that a declining legume cover could return to the soil, over 2–4

years after planting, the equivalent of 13 kg magnesium, 121 kg nitrogen, 9 kg phosphorus and 30 kg potassium (Anon., in Turner and Gillbanks, 1974, p. 20). However, Han and Chew (1982) measured nutrient contents in remain legume covers growing under young palms on Selangor soil and these were 31–47 kg/ha Mg, 227–386 kg/ha N, 16–34 kg/ha P and 129–223 kg/ha K. In contrast, grass cover contained only 29, 109, 19 and 156 kg/ha respectively. Gray and Hew (1968) showed that with natural ground cover, the application of compound fertiliser (8% N, 4% P, 14% K and 2% Mg) gave a 13% yield increase in the first 6 years. The same increased yield could be obtained by establishing a legume cover, and with this, the fertiliser only gave a further 3% increase. It is not possible from this to deduce the exact amounts of nutrient release, but there must have been a substantial input from the cover as it declined with the growth of the palms. The nutrient content in four leguminous species on Serdang and Selangor soil series was measured by Han and Chew (1982). These differed in their success as covers, depending upon the criterion of success selected, and none was ideal in all ways. They were sampled at 20 months after planting of palms and covers, including roots to 10 cm. Results were expressed on kg per hectare basis after deducting areas not carrying cover crop. Maximum nutrient values were largest for *Centrosema pubescens*, at 386 N; 19 P; 132 K and 42 Mg, all in kg/ha, except for K, which was largest in *Calopogonium caeruleum*. Recently, Mathews and Leong (2000) compared a new legume, *Mucuna bracteata*, and a mixture of the three classical legumes (Table 10.5). The nutrients in both covers at 2 years were much larger than any figures quoted above, although the only significant difference between them was that the conventional covers immobilised more phosphorus than did the *Mucuna*.

A full comparison of these different cover plants was made by Teoh and Chew (1980) in the presence of different levels of nitrogen fertiliser (Table 10.4). The *Mikania* competitive effect is clear, and its competition for nitrogen may be due to a compound in it that inhibits nitrification in the soil. The best cover on the whole was legumes plus naturals, which gave the largest yield at the middle nitrogen level.

The benefits of legume covers seem to be relatively less in the seasonal climate in West Africa than elsewhere. It has been suggested that this is because the vigorously growing legume competes with the palms for water (Ochs and Daniel, 1976). However, it is hard to see why the equally vigorous natural cover, which includes some deep-rooted shrubs that will remain green until well into the dry season, should transpire less. It is accepted that palm yields are greater with bare soil (or with crops) than with full covers in these climates (Daniel and

Table 10.5 Dry matter production and nutrients immobilised and recycled by legume covers

	Treatment		SE
	Conventional covers ^a	<i>M. bracteata</i> ^b	
Total dry matter (t)	12.41	11.49	1.60
N in total dry matter (kg/ha)	232.0	260.8	33.7
P in total dry matter (kg/ha)	28.3	19.2	3.3
K in total dry matter (kg/ha)	187.8	156.5	23.3
Mg in total dry matter (kg/ha)	36.9	24.8	5.8

^aMixture of *Pueraria phaseoloides*, *Calopogonium mucunoides* and *C. caeruleum*.

^bNew legume: *Mucuna bracteata*.
After Mathews and Leong (2000).

de Taffin, 1974), and this is almost certainly an effect of water stress. However, this is not relevant to the debate on natural vegetation versus perennial legume cover. The use of an annual short-season legume that would reseed itself every year when the wet season arrived might be a useful alternative (Corley, 2001), if the shade under young palms permitted it to grow sufficiently. Caliman (1992) discussed the water balance in this situation (see Section 3.2.3) in relation to the cover crop. He suggested that the legume cover should be kept, but it should be reduced in area by increasing the size of the weeded circle, and/or by killing a strip in the interline centre with herbicides. If this was done before the dry season, the dead cover crop could be left as a mulch (unless it was a fire hazard). The cover spread back when the rainy season started; *Pueraria* spread most quickly, but *Calopogonium* had the greatest drought resistance and ability to grow in shade. Such a strip has also been recommended as a permanent machine road (Section 10.2).

The sequence from the originally sown legumes to a stable cover vegetation under mature palms differs between Africa and Asia (Hartley, 1988), in that it may be easier to maintain the legumes in the former for a number of years. This may simply be a consequence of the larger crowns of the Asian palms and the deeper shade at ground level.

The establishment of leguminous covers is sometimes assisted by the use of pre-emergence herbicides. Normally, legume seeds should be sown on ground already cleared of other vegetation by ploughing, cultivation or spraying. The weed-free period can be prolonged by

hand-weeding, unless labour shortages make this difficult, in which case glyphosate or other herbicides are used. Mechanical weeding is very convenient if the conditions are satisfactory. Rankine and Fairhurst (1998b) give a list of noxious and of beneficial natural plants, the former being weeds that must be eradicated at this stage. Chung and Balasubramanian (1996) considered that weed infestation was often neglected in planting. They pointed out that one of the purposes of planting legumes is to suppress weeds, but the legumes cannot do this if they are sown into weed-infested ground (see Section 8.3.3.3). They regarded the latter as largely due to poor land preparation in replanting, and to zero-burning underplanting, and they urged that weed suppression is essential to good establishment.

10.1.2.4 Nitrogen fixation by cover plants

Most of the fixation of nitrogen takes place while the palms are still young, so it is discussed in relation to young palms. The total mass, leaf area index and land area of the legume are then much greater than subsequently, and the total insolation is also much larger than under older palms; Squire and Corley (1987) found that the palms intercepted 80% of the light after only 5 or 6 years' growth, and plantations become steadily more precocious with time.

Agamuthu and Broughton (1985) carried out a study of nitrogen cycling under leguminous covers, by sequential sampling of plots laid out under palms with different cover. Lysimeters were installed so that the leaching water could be collected from each plot. The fastest-growing cover was a *C. pubescens* and *P. phaseoloides* mixture. Atmospheric input was large, at 21 kg/ha nitrogen per year. It was assumed that denitrification did not occur on this acid soil. Overall, the legumes reduced leaching from the soil by 63 kg/ha. They accumulated a total of 176 kg/ha in their foliage, which was returned to the palms when the covers died down. The variation in the amount of nitrogen found in legume covers is large, as growing conditions must vary widely. More research on nitrogen fixation rates by legume covers is needed, especially in relation to the size of the palm canopies and the light intensity at ground level.

There is a long history of research into nitrogen fixation by non-symbiotic rhizosphere bacteria, but the results have so far been inconsistent or difficult to replicate in the field (Tinker and Nye 2000, p. 192). Amir *et al.* (2001) reported substantial uptake of fixed nitrogen by palm seedlings in the glasshouse, following inoculation with *Azospirillum* bacteria, but this needs confirmation.

Table 10.6 Effect of degree of pruning of palms on their yields

Treatment	Bunches (no./ha per year)	Mean bunch weight (kg)	Bunch yield (t/ha per year)
Nigeria ^a			
No pruning	803	10.0	8.01
Dead leaves only, annually	813	10.4	8.51
Pruning to one leaf below the bunch, 6 monthly	726	9.9	7.16
Pruning to flowering inflorescence, annually	699	9.7	6.76
Malaysia, Inland ^b			
Leaving 40 leaves	1,415	16.5	25.24
Leaving 32 leaves	1,344	14.5	24.48
Leaving 24 leaves	1,287	13.9	20.50
Leaving 16 leaves	1,032	11.2	13.29
Leaving 8 leaves	212	6.9	4.35

^a Adjusted means for 6 years (pretreatment yields available for 4 years).

^b Bunch yield for 2 years, other data for the second year.

After Hartley (1988, p. 442; see for original authors).

10.1.3 Maintenance of mature plantations

10.1.3.1 Maintenance of plant cover

Hartley (1988, p. 433) suggested that as the legume cover declines, weeding out other species becomes steadily more expensive, and it may be better to accept a mixed natural/legume cover. Tan and Ng (1982) even suggested that such a mixture could be used from the start, and this does sound attractive, especially for improved soil conservation on slopes, and because it contains as much nutrient as a pure legume cover. Hartley (1988) regarded this as less suitable for the Asian plantations, but only because of the ease with which a moderately pure legume stand can be obtained and preserved. With present labour shortages a pure legume cover may be more difficult to manage, and a mixed cover may be better.

Ultimately, the legume cover will be shaded out, and the vegetation that replaces it in the Far East is the fern *Nephrolepis biserrata*, with various grasses such as *Paspalum conjugatum* and *Axonopus compressus* (Plate IIIA). The creeper *Mikania* often appears, but it has no adverse effects if it is only a small percentage of the vegetation. The ferns and other plants can be given a light slashing occasionally, and the fern fronds form a thick protective mat on the soil. The other species that may become established were discussed by Hartley (1988), but their practical importance seems small.

10.1.3.2 Maintenance of palms

At one time there was a practice of pruning up to a bunch. This allowed the ripening of the next bunch to be observed properly, but it resulted in many green leaves being cut off, well before they would have senesced naturally (Table 10.6) (Hartley, 1988). The ability to see a ripening bunch clearly is a considerable advantage, and makes it more likely that the bunch will be harvested at about the correct time in areas with tall palms (Section 10.4.3). There is a trend in Malaysia towards progressive pruning, in which the harvesters prune regularly on their rounds, and are paid for this. This appears more effective than pruning only once or twice a year, which encourages overpruning. Pruning only those leaves that need to be removed to gain access to a ripe bunch may leave 35–40 fronds, and will involve cutting few green fronds.

The return of the pruned fronds to the ground, stacked in frond piles in alternate interlines, is a standard part of palm maintenance. This is taken as part of the inner nutrient cycle (see Section 11.1.4) and also part of the carbon cycle. Henson (1999c) concluded that about 9 t/ha of dry matter was delivered back to the soil surface each year under mature oil palms. This is probably the main input of carbon to the soil, and thus may be a major factor in determining the equilibrium soil organic matter level. However, Khalid *et al.* (1998) found that the organic matter in the soil under frond piles was not consistently larger than elsewhere

in the plantation. This suggests that most of the decomposition of the fronds occurs above ground, and their carbon residues rarely enter the soil ecosystem at all. If this is correct (and it will need more testing), it should be possible to remove the dead fronds as biomass (see Section 13.6.1) without causing any damage to the soil, other than the loss of nutrients, which can easily be replaced. It also raises the question of whether the same is true of fronds that are not stacked, but left spread over the soil surface. The epiphytes that develop on the palm trunk may be removed, as loose fruits can easily be caught on them during harvesting, along with seeds of weeds such as *Clidemia hirta* and *Asystasia*.

The return of empty fruit bunches (EFB) and palm oil mill effluent (POME) to the fields is an essential part of nutrient recycling (see Section 11.7.2.1), and the mulching effect of EFB is also valuable, especially for older palms where the cover growth has become very thin. Burning EFB is now not permitted in Malaysia, so it has to be distributed to the fields. The use of EFB was shown by Loong *et al.* (1988) to give good responses of around 22% in immature palms on both inland (Rengam) soil and coastal (Briah) soil, with applications of 30 t/ha and 25 t/ha, respectively. With mature palms, there was again a good response on Rengam soil, but only with heavy applications of about 70–90 t/ha EFB. On Selangor coastal soil the mulched treatments gave about 10% less yield than the controls. The lack of a positive response can be explained by the fact that this soil is well supplied with water by a high water table, and has excellent chemical fertility. However, it is very difficult to explain the clear reduction in yield; possibly the decaying organic matter increased the anoxic conditions in the soil. Yields were not affected by whether EFB was spread in the interlines or left in heaps. Gurmit *et al.* (1999b) noted that spreading EFB gave moderate responses of 19 and 36% on two Lunas series soils, and 13% on an Akob series soil. Lim and Zaharah (2000) studied the decomposition process of EFB applied in single or double layers, and at up to 75 t/ha with various fertiliser treatments. The loss of dry weight was at an exponentially decreasing rate, with 50% lost after 3 months and 70% after 8 months. Addition of fertiliser nitrogen, but not potassium, increased the decomposition rate. Release of potassium was very rapid, with 90% being lost after 6 months, but no release of EFB-nitrogen was detected.

The distribution of EFB is a labour-demanding task and the mechanisation of this is now essential. Salleh *et al.* (1990) reported that the use of minitractors and trailers (RM50/ha) was much more economic than the use of standard-size tractors and trailers (RM170/ha). The increase in yield over a whole plantation from adding

37.5 t/ha was 5%, and this also saved the fertiliser equivalent of one-third of the normal application. Using the empty fresh fruit bunch (FFB) lorries to return EFB to the fields gave a considerable saving. The whole operation saved RM120/ha in years when no capital expenditure was needed; full details of capital expenditure are given by Salleh *et al.* (1990).

Siregar *et al.* (2002) tested again the idea of composting EFB with added nitrogen as urea. The maintenance of a correct moisture level of about 60% required control of water additions and temperature. The paper claims that the reduction in weight of the EFB during composting was a benefit in reducing the cost of transport. However, the input of carbon to the soil is usually seen as a virtue of EFB addition, so the benefit must assume that the compost has a longer residence time than the original EFB. There are no data on this. This paper points to possible nutrient losses, which emphasises that all composting process research should include an element balance.

There has been much interest in applying both EFB and POME together, after a combined composting process (Lord *et al.*, 2002, and Schuchardt *et al.*, 2002a, b). This is partly justified by the problems inherent in spreading EFB alone: transportation costs, the long period of decomposition, pollution by the remaining oil, and the encouragement of snakes and beetles. It has been shown repeatedly that EFB will rot far quicker if N is added, as its own C/N ratio is around 50 (Gurmit *et al.*, 1999b). The use of POME also has problems, mainly high transport costs, so that it tends to be applied to the minimum area close to the mill, and also the production of methane from ponds. It contains 400–1200 mg/l N (Lord *et al.*, 2002), or an average of 800 g N per tonne POME. This corresponds to about 1/3 t EFB, which contains about 56 kg C, and about 2.3 kg N. It is therefore sensible to combine the two in the ratio in which they are produced, as the average composition indicates a final C/N of about 9, if half the carbon, but none of the N, is lost during decomposition.

In these processes the POME is sprayed over the EFB either under a roof or in the open, at such a rate that both wastes are used up together. Schuchardt *et al.* (2002a) used a simple process of heaps in the open, but with a 'windrow turning machine' that mixed the rotting material. The final material was screened into compost and larger material used for mulching. They also tested 'rotting boxes'. The local rainfall was 2000 mm, and the addition rate about 3 t POME to 1 t EFB, so the total liquid added was considerable, but the heat of decomposition evaporated most of it. The composting time seemed to be variable from 3 weeks to 12 weeks,

producing compost with C/N with high values of 15–20. Lord *et al.* (2002) used a more complicated three-stage system, enclosed, open and covered, the overall composting time being 23 weeks.

These systems produced a no-discharge mill. An Schuchardt *et al.* (2002a, b) claimed that the cost of the finished compost is €15 per tonne, whereas the nutrients contained in it are worth €25. Lord *et al.* (2002) calculated that the annual saving, in a 40 t/hr mill, was up to US\$156,000. This is clearly a technique that is becoming practical on a large scale, after more tentative work earlier. The economics will have to be worked out on a larger sample of mills before one can be sure that it is profitable, but the attraction of having no polluting discharges will be worth a great deal.

10.1.3.3 Circle and path maintenance

The purpose of the paths is to increase accessibility. The purpose of the circles is two-fold. In the early years the weeded circle prevents the young palm suffering from serious competition, above or below ground. Later, the purpose of the circle is to allow access for harvesting and fruit collecting. Originally, all weeding and slashing was manual. The drive for greater labour efficiency has taken two forms: the use of tractor-drawn machinery for keeping covers in check on paths, and the use of herbicides where the cover (and weeds) are to be eliminated in the circles and paths. Another useful labour-saving system is to place a black plastic mulch around young palms (Plate 8.3).

The use of herbicides has increased greatly since the 1980s, although Rankine and Fairhurst advised against their use for the circles of immature palm, especially phloem-translocated herbicides such as glyphosate. Spraying of paths, and spot-spraying of selected weeds by knapsack or controlled droplet size sprayers are standard operations (Rankine and Fairhurst, 1998b, c). Detailed methods and machines have been discussed by Nathan (2000) in general terms, and by Mustafa (2000) for one particular plantation.

10.1.4 Care of plantation with cultivation and intercropping

Intercropping and intergrazing were discussed in Chapter 8 (see Section 8.4.3), as the decision on whether to use these options is best taken before the palms are planted. Intercropping is of little interest to large plantations, as the cultivation of mixed crops always causes a managerial problem, which is why monoculture is so ubiquitous in developed agriculture. There

are therefore few good records on how intercropping can be used in the most efficient way. Simple cultivation of the soil as an alternative to sowing a legume is often used (Rankine and Fairhurst, 1998b). There is usually a much larger palm yield with cultivation, i.e. earlier entering into bearing where the soil has been cultivated and has remained bare or with annual crops. However, subsequent yields may be lower than where a legume has been sown immediately, as shown by Chew and Khoo (1977). This may be due to nutrient depletion by crop offtake, particularly in early experiments with no fertiliser, because the cultivation and exposure of the soil to more intense wetting–drying cycles must lead to loss of soil organic matter and nitrogen. In addition, there will be less evapotranspiration of water where the soil is bare, and hence greater leaching. Alternatively, the later superiority of a legume cover over bare soil may be due to a genuine input of fixed nitrogen from the legume covers, or the legume may help to hold nutrients from a replanted stand until the new stand is large enough to absorb them (see Section 11.7.1).

In a seasonal climate simple cultivation under the crop may give a continued yield increase (Sly *et al.*, 1963), suggesting that the reason for the yield decline after intercropping is indeed a result of nutrient losses in the crops. If so, fertiliser dressings should lengthen the period of high production, but this does not appear to have been directly tested. Kowal and Tinker (1959) showed by soil analysis that the chemical fertility remained largest under natural cover, intermediate under a legume cover and least under arable cropping over a number of years. They suggested that the natural cover was the best for recycling nutrients from the subsoil into the topsoil, as happens during shifting cultivation.

10.1.5 Labour requirements for field operations

Comparing production costs in different countries is difficult. The important figure is the total cost of production per tonne of oil, but differences in accounting practices and the variations of exchange rates make such comparisons unreliable. Some relative comparisons are given in Chapter 14. By comparing labour requirements in man-days, the complications of the exchange rate aspect are removed, but there are still several ways in which labour use can be expressed, which may be confusing. Thus, for individual operations some reports quote man-days per round, but without mentioning how many rounds per year are required. Others quote tractor-days, without giving the power of the tractor, or

Table 10.7 Approximate labour requirements for field operations

		Labour requirements (man-days/ha)						
		Malaysia		Indonesia	Thailand	Ghana	Ivory Coast	Colombia
Operation	Sources	1	2	3	4	5	6	7
<i>Weeding: immature areas</i>								
Circle weeding		2.4	—	2.0	1.7–2.8	2.0	6–9	—
Interline weeding		2	—	11	2.8–4.0	3.6	2.5	—
<i>Imperata</i> control		0.5	—	—	0.2–0.9	—	7.5	—
Cleaning palm crowns		—	—	—	—	—	1.5	—
<i>Weeding: mature areas</i>								
Circle weeding		0.17–0.4	—	0.7	0.2–0.7	1.5	3–6	—
Interline weeding:								
chemical		0.25	—	1.0	0.6–1.4	1.1	2.4	—
manual		—	—	3.8	—	3.1	—	—
<i>Pest and disease control (if needed)</i>								
Pest and disease census		0.1	0.03	1.0	—	0.03	0.04	0.03
Rat baiting, 5 rounds/year		0.4	0.22	0.7–1.3	0.4–0.6	—	—	—
Trunk injection of insecticide/round		0.3	0.15	1.1	0.6	—	—	1.33
Insecticide fogging/round		—	—	—	—	0.2	—	0.03
<i>Other operations</i>								
Pruning		—	0.3–1.3	4.9	1.3–5.4	1.6–3.1	—	0.7
Fertiliser application:								
manual		—	1.5–3	1.3–2.1	1.5–2.3	0.6	—	0.6
tractor		0.2	—	—	0.35	—	—	0.2
EFB mulching:								
manual spreading		—	1–1.5	—	2.8	—	—	—
mechanical		—	0.1–0.3	—	0.5	—	—	—
<i>Harvesting and fruit transport</i>								
Total		8–11	—	13.7	12–24	—	—	—
Separate operations:								
cutting		4–8.5	—	—	4.3–7.2	—	—	—
loose fruit collection		—	—	—	—	—	—	—
In-field transport:								
minitractor		0.9–1.7	—	—	—	—	—	—
‘iron buffalo’		—	—	—	1.3–5.7	—	—	—
buffalo		3.8	—	—	—	—	—	—
<i>Harvesting, fruit transport, processing (tFFB per man-day)</i>								
Total		1–1.9	1.2–2	1.7	—	—	—	—
Separate operations:								
cutting		3–4.8	—	—	3.5–5.5	2.3	—	—
loose fruit collection (t LF/man-day)		—	—	—	—	0.25	—	—
In-field transport:								
minitractor		15–18	—	—	7.4	—	—	—
‘iron buffalo’		—	—	—	—	—	—	—
buffalo		3.8	—	—	—	—	—	—
wheelbarrow		—	—	—	—	2.1	—	—
Processing		8.5	—	7.0	—	—	—	—

Sources 1: Pamol Plantations Sdn Bhd; 2: Rankine and Fairhurst (1998c); 3: London Sumatra; 4: Univanich Group; 5: Benso Oil Palm Plantations; 6: Jacquemard (1998); 7: Unipalma. LF = loose fruit.

the number of workers in a tractor team, and there are many other examples of inconsistencies that make accurate comparisons impossible. For a particular task, man-days/ha per year is the easiest unit of comparison.

Table 10.7 gives some information on the number of man-days required per hectare per year for various field operations, compiled from several sources. So far as we know, the figures are in man-days/ha per year, except for those harvesting figures, in the last section of the table. However, some uncertainties remain, and the figures should be used with caution, as an indication only. Harvesting costs are expressed both in man-days/ha and t fruit/man-day. The allocation of labour for harvesting is particularly variable: harvesters may or may not stack fronds, loose fruit collection may be organised as a separate operation, and so on. The figures for pest control operations indicate the costs if they are required, but as noted in Chapter 12, pest outbreaks are sporadic and unusual, and in many years no treatment will be needed in most environments.

What does seem clear is that labour use is lower in Malaysia and Thailand than in Indonesia or the Ivory Coast, and that there has been a greater emphasis on mechanisation of the industry in the former countries. The high usage of labour in Indonesia reflects the ready availability of labour at low cost, and strict insistence on high management standards. For total labour requirements, Davidson (1993) gave a figure of 7.5 ha/worker for Malaysia in 1991. This had increased from 4 ha/worker in 1951. Over the same 40-year period yields/ha had quadrupled, so in 1991 production was 30 t oil/worker, compared with 5.7 t in 1951. Hectares per maintenance worker increased from 8 in 1951 to 30 in 1991, and t oil/factory worker per year increased massively from 33 to 537. Harvesting productivity showed the smallest increase, from 138 t FFB/harvester per year to 329. This reflects the fact that the cutting, collection and initial loading operations are still entirely manual, and that fruit transport is the only part of the harvesting operation to have been mechanised.

10.2 FIELD MECHANISATION

The comparative costs for estates that still depended largely on manual labour and those that had been mechanised were investigated by Stringfellow (1999) (Table 10.8), and showed important savings on all tasks, except for harvesting of fruit, when the estate was mechanised (Section 10.4.6). There may be associated capital costs, because machine access paths are essential. Hilly soils may need terracing as a routine to allow access for wheeled

Table 10.8 Labour costs (%) and total input values (%) for traditional labour-intensive and for mechanised estates in Malaysia in %

Task	Labour-intensive	Mechanised
Labour cost (%)		
Harvesting and collection	76	93
Transport to mill	9	4
Weeding	10	2
Manuring	5	1
Total input (%)		
Labour	52	37
Fertiliser	43	47
Others	5	16

After Stringfellow (1999).

machines, and peat soils may need extra compaction or drainage to give the necessary bearing strength (see Sections 8.3.5 and 8.3.6). The process of mechanisation should be fully integrated with the general management strategy of a plantation. Bek-Nielsen *et al.* (2000) have given a useful oversight of mechanisation and management at United Plantations in Malaysia.

Considerable advances have been made in this subject, especially in the past few years, and it is possible to believe that the oil palm industry will make considerable savings (Rahim Shuib *et al.*, 1990). It may move to precision agriculture (Chew, 1998) as mechanisation becomes fully accepted and implemented. The areas of immediate priority, where major impact is already occurring, are harvesting and collection (Ahmad Hitam and Ahmad Zamri, 2000), fertiliser application, and pesticide and herbicide application (de Souza, 2000).

10.2.1 Mechanisation of fertiliser spreading

Standard fertiliser distributors can now be used routinely, and Lai (2000) discussed types and costs of modern machines designed for estate operation. His recommendation was the turbo-spin air-assisted spreader, which gives a spread width of up to 25 m. A bunch ash spreader is now also available that handles this light and powdered material satisfactorily, although it is no longer used in Malaysia because bunch refuse cannot be burned there. An estate may need different types of spreader, for example a narrow machine for work on terraces, and there needs to be a good basic road system if mechanisation is to be a success (Teo, 1999). So far, fertiliser spreaders are used mainly on mature palms, with the fronds well clear of the ground, as otherwise they deflect the stream of fertiliser pellets. Some new

developments are needed for young palms. Ooi and Sim (1997) reported that mechanisation of fertiliser spreading increased worker productivity by a factor of ten, and reduced costs by 52%. They noted that mechanisation also meant a higher wage for the workers and a lower physical load, with consequent improvements in worker morale. The real surprise is how slowly this fairly simple development has spread through the industry. The need for great accuracy in spreading is less than in arable agriculture, because of the size of the individual plants, and some unevenness of the machine roads is acceptable. It is now becoming fairly common practice elsewhere to link the spreader with a Global Positioning System (GPS) and possibly a Geographic Information System (GIS), so that there is a digital record of how much was applied to each spot, and this is being evaluated in Malaysia (Tey and Chew, 1997; Ooi and Tey, 1998). Aerial application of fertiliser is effective, but seems to be less popular now (see Section 11.9.3) probably because of errors in the position of applications.

The most difficult problem in nutrient management is the recycling of plantation wastes (see Section 11.7). Mechanisation is desirable when recycling EFB back onto the land and spreading it throughout the plantation (Chee and Chiu, 1999). It can be returned by the lorries that carry FFB to the mill, dumped on the edge of the field and spread further with minitractors and trailers, using a grabber for loading. A special 3 t spreader is also available. However, if labour is available manual application may be cheaper than local mechanised application (Chee and Chiu, 1999). The handling of EFB is relatively simple (Plates VD, E), in returning it to a similar area from which the FFB originated. The most expensive part of the task is in spreading it reasonably uniformly over the soil surface, or around the palms if these are young. It is more difficult to distribute the POME, and several systems result in a heavy loading within a small area, well above the possible nutrient-absorbing powers of the palms (Tayeb Dolmat *et al.*, 1988; Lim K.H. *et al.*, 1999). It is easiest to apply tank-digested POME, after biogas has been recovered and the pH is neutral. The best way appears to be to use tankers and high-pressure pumps to distribute it reasonably uniformly around the plantation, so long as the actual application rate is kept under careful control. At the least, the application per hectare in any area should not exceed a reasonable total nutrient need by the palms in the area (see Section 11.6.1).

10.2.2 Weed and pest control

Mechanical weed control consists of rotary slashing of the interlines. This helps to control erosion and

waterlogging. Chemical herbicides and pesticides can be applied with a conventional knapsack sprayer. With the low volumes of pesticide now used as part of integrated pest management, a controlled droplet applicator (CDA) machine is more efficient. With this the working rate can reach 4–6 ha/man-day. Recently, a new mistblower has become available, with a higher work rate (Summugam, 2000). The CDA unit can also be mounted on a small tractor pulling a small tanker, and can apply spray accurately. When spraying paths and circles, it can cover 12–15 ha/day. For even higher output the fully mechanised tractor-mounted boom sprayer is available for overall spraying of the interrows. When linked with GPS/GIS technology the correct amount can be applied where it is needed, if the guiding information on pest infestation or weed density is available in digital form.

10.2.3 New planting and replanting

The felling of forest trees can be undertaken by machinery (see Section 8.3.3), although there will usually be a few large or difficult trees that are felled with chainsaws. The windrowing of the felled trees will normally be done with the tractor that was used to fell them. The felling and chipping up of old palms is also a mechanised process, using a modified sharpened bucket on an excavator. The preparation of holes for planting is done with a tractor-mounted digger.

10.3 IRRIGATION

The supply of water from the soil to the palm is described in Chapter 3, and the physiological effects of drought or water stress on palms are discussed in Chapter 4. Irrigation during periods of drought has been shown to increase oil palm yields (Table 10.9). The increases are predominantly due to changes in bunch number rather than mean bunch weight, as expected from what is known of palm physiology (see Sections 4.3.3.3 and 4.4).

10.3.1 Methods of estimating irrigation requirements

Decisions on whether irrigation is likely to be profitable, and on when to operate the system once it has been installed, both require information on the degree of water stress suffered by the palms. In the first case, estimates of drought frequency and duration from long-term weather data will be needed. In the second case, daily or weekly measurements of the severity of stress will be required. Water stress can be measured or

Table 10.9 Details of irrigation experiments: water deficit, age of palms, control and irrigated values and percentage increase, for FFB, bunch and mean bunch weight

Location	Water deficit ^a (cm)	Age of palms (years)	FFB yield (t/ha per year)				Bunch no./palm per year			Mean bunch wt (kg)			Ref.
			Contr.	Irrig.	Incr.	% Incr.	Contr.	Irrig.	% Incr.	Contr.	Irrig.	% Incr.	
Ivory Coast	660	4–8	6.4	14.5	8.1	125	8.7	15.8	82	5.5	6.8	24	1
Benin	582	8–11	16.1	23.4	7.3	47	7.2	9.5	33	15.7	17.4	11	2
Ivory coast	275	3–5	6.5	11.5	5.0	76	10.6	17.1	61	4.3	4.7	9	3
Malaysia	?	13–16	30.7	34.1	3.4	11							4
Malaysia	82	5–10	24.7	25.3	0.6	2	13.6	14.1	3	13.1	13.0	–1	5
Malaysia	?	11–14	24.6	32.1	7.5	30	7.5	9.0	20	22.6	25.0	10	6
Malaysia	38	5–14	25.4	30.1	4.7	19							7
Ivory coast	572	5–10	16.6	22.3	5.7	34	10.6	14.3	35	10.9	11.0	1	8
Colombia	130	5–7	14.2	20.3	6.1	43							9
Colombia	266	4–8	14.2	19.3	5.1	36	9.5	12.5	32	10.5	10.8	3	10
Colombia	245	3–5	7.2	11.2	4.0	55	14.0	11.2	25	5.6	4.6	22	10
Malaysia	164	5–10	29.2	32.6	3.4	12							11
Thailand	214	8–14	18.7	24.5	5.8	31							12
Thailand	214	10–13	19.5	23.9	4.4	23							12
Malaysia	210	16–20	20.9	24.0	3.1	15	6.4	5.6	14	24.6	25.0	2	13
Ecuador	?	?	22.4	28.3	5.9	26	12.2	14.4	18	17.2	18.3	6	14

^aIRHO definition, maximum reached in one season.

References: 1: Desmarest (1967); 2: de Taffin and Daniel (1976); 3: Ochs and Daniel (1976); 4: Chan (1979); 5: Corley and Hong (1982); 6: Chan *et al.* (1985); 7: Chuah and Lim (1989); 8: Prioux *et al.* (1992); 9: Corley (1992); 10: Unipalma (unpubl.); 11: Lim *et al.* (1994); 12: Palat *et al.* (2000); 13: Kee and Chew (1993); 14: Mite *et al.* (2000).

estimated by a variety of different methods. Direct measurements can be made by monitoring stomatal opening with a porometer, but Palat *et al.* (2000) considered that the method was too laborious and too imprecise for practical irrigation management. The usual method involves the calculation of soil water deficit (SWD), but as explained in Section 3.2.2.3, this can be done in various ways, leading to several different values of the water deficit.

10.3.1.1 Rainfall and evapotranspiration

The essential condition that leads to the development of a water deficit occurs when actual evapotranspiration (E_a) exceeds rainfall. The first question that arises is how to estimate E_a for routine use. The methods for direct measurement (lysimeters, neutron probe readings of soil water content) are not suitable for day-to-day plantation practice. The IRHO (Institut pour Recherche sur les Huiles et Oléagineux) method for estimating SWD (Surre, 1968), widely used in the oil palm industry, estimates potential evapotranspiration (E_o) from the number of rain-days per month (Section 3.2.2.3). Water deficits calculated by this method are included in Table 10.9, but the method cannot predict short-term irrigation requirement and was never intended for that purpose. Figure 3.2

explains how the water deficits vary during a long drought, with assumed daily E_o of 5 mm/day.

The standard method for estimating E_o is to use the Penman–Monteith equation (see Chapter 3) or pan measurements, but depending on pan design, these may have to be corrected to give E_o . The E_c of the crop is rarely exactly equal to the potential figure, the necessary correction factor being known as the ‘crop factor’. For oil palms well supplied with water, Henson (1995b) found that E_c was approximately equal to E_o , giving a crop factor of 1, but falling to about 0.9 when solar radiation exceeded 20 MJ/m² per day (presumably because of stomatal closure under large vapour pressure deficits; see Section 4.3.3.2). Ling (1979) also found that E_o was about equal to E_c for an immature palm in a lysimeter, but class A pan evaporation was consistently lower. Pabon Silva (1985) used a crop factor of 0.75, but the basis for this was not clear.

A decision has to be made on whether to use hourly, daily, weekly or monthly data for estimating SWD. Allen *et al.* (1994) recommended using hourly data in the Penman–Monteith equation, but for estimating irrigation requirements for oil palm, weekly data should usually be adequate, given that total evapotranspiration in a week is unlikely to exceed 40 mm, and the critical deficit for oil palm is almost certainly greater than that

(see below). Monthly data will not be good enough, because it is quite possible for the first 3 weeks of a month to be dry, but for heavy rain in the last week to exceed the total Eo for the month, so that the monthly totals indicate that there was no drought during the period.

As a further improvement, rainfall should be corrected for runoff losses; these tend to occur during very intense rain, when the infiltration capacity of the soil is exceeded (see Section 3.2.2). The amount of runoff therefore depends on rainfall intensity and on soil infiltration capacity, which in turn depends partly on the soil water content (Maene *et al.*, 1979; Kee and Chew, 1996).

The potential water deficit (PWD) is the cumulative difference between Eo and rainfall (plus irrigation, if any), and this has been used as a signal for irrigation. For example, Palat *et al.* (2000) irrigated whenever the PWD exceeded 30 mm, so that the palms were always very well supplied with water.

10.3.1.2 Soil moisture reserves

Using a simple balance between rainfall and Eo overestimates the degree of stress, because the soil holds water, some of which is freely available to the plant. The available water capacity (AWC) is the amount of water (usually expressed in mm) held between field capacity and permanent wilting point (see Section 3.2.2). The IRHO method assumes an AWC of 200 mm, in the absence of other information, but actual AWC varies over a wide range, for several reasons.

- *Soil type:* AWC varies greatly between different soils. Foster *et al.* (1984a) found values ranging from 73 to 239 mm/m for Malaysian soils, and over 400 mm/m for peat, which can hold large amounts of water by swelling.
- *Soil depth and rooting depth:* The total water available to the palm depends on rooting depth. This is often assumed to be no more than 1 m, and on some soils this may be correct, but Rey *et al.* (1998) used neutron probe measurements of soil moisture to show that oil palms extracted water from below 5 m in Ivory Coast. Although AWC for this sandy soil was only about 80 mm/m in the topsoil, and 50 mm/m at depth, the total AWC for the 5 m profile was 250 mm. The same amount of AWC at different levels is not completely comparable, because the lower root density at depth reduces the water availability. On some soils, rooting may be restricted to the surface layers, despite a deep profile, by a semi-permanent water table. If the water table drops

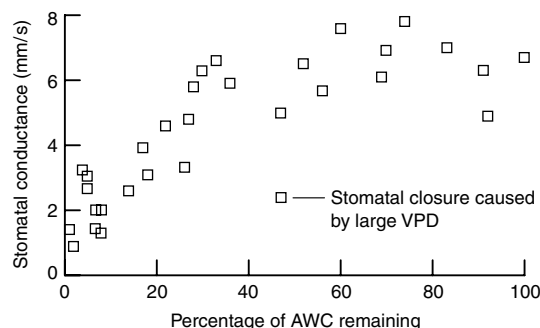


Fig. 10.3 Stomatal conductance in relation to percentage of available water capacity remaining. (After Rey *et al.*, 1998.)

during drought, stress may develop rapidly (Chuah and Lim, 1989).

The IRHO method also implicitly assumes that no stress occurs until all the available water has been used. This is plainly not true. As the soil dries and water content falls towards the wilting point, remaining water is more tightly held, and extraction by the plant roots becomes very slow. Using stomatal opening as an indicator of stress, Rey *et al.* (1998) estimated that about 70% of the total AWC was easily available to the plant (Fig. 10.3), in agreement with earlier work in the same environment (Wormer and Ochs, 1959). Thus, for mature palms on this particular soil, the 'critical deficit', beyond which the palms started to suffer, was about 175 mm, and there may be little benefit from starting irrigation until this deficit is reached. On shallower soils, or for young palms with a less extensive root system, the critical deficit may be much smaller. On a shallow, lateritic soil in Malaysia, stomatal opening and spear leaf elongation rates of 1-year-old palms were reduced at deficits of less than 60 mm (Henson and Chang, 1990; Henson, 1991a). Many of the factors that affect the calculation of irrigation need are uncertain, so it is wise to apply more than the calculated amount if it is possible.

10.3.2 Methods of irrigation

10.3.2.1 Type of equipment

A variety of different irrigation methods has been used on oil palms. The simplest and cheapest method is to control the water table level by flooding, or blocking drains (Lim *et al.*, 1994), but this is only applicable in

relatively flat, low-lying areas. Other methods involve significant capital investment in pumps and piping.

Corley (1996) suggested that drip irrigation may be less effective than sprinkler or flood irrigation, for two reasons. First, it does not wet the whole soil surface, so that part of the root system of a nursery palm may be droughted (Henson *et al.*, 1992). If so, it may send a signal to the leaves, causing stomatal closure, even though the palm is well supplied with water from the remainder of the root system. Secondly, drip irrigation will have less effect on atmospheric humidity than methods such as sprinklers, and it has been shown that oil palm stomata close in response to low humidity (see Section 4.3.3.2). However, when Palat *et al.* (2000) compared drip, sprinklers, microsprayers and contour furrows, they found no significant differences in yield response among the methods, and there was a suggestion that drip might actually be more effective than other methods. The concentration of applied water in particular locations may allow the plant's root system to develop more intensively there and use the water more completely, as root system growth responds to local increases in water and nutrients.

10.3.2.2 Frequency and quantity of water

Drip systems are normally operated on a daily basis, replacing daily Eo, but with other systems it is usually more convenient to apply larger volumes of water less frequently. Frequency is probably not important, provided that the interval is not so long that the critical deficit is exceeded.

In most irrigation trials, sufficient water has been applied to replace Eo completely, either estimated as discussed above, or often assumed to be a constant 5 mm/day. However, Palat *et al.* (2000) found that the response to irrigation was not necessarily linear: the lower rate of irrigation (150 litres of water/palm per day, equivalent to 2.1 mm) gave a response of 3.9 t FFB/ha. The higher rate, 4.2 mm, yielded only an additional 1.9 t/ha. This is to be expected, as response to irrigation is normally curvi-linear. Where water supply is limited, therefore, partial replacement of Eo over a large area will make better use of it than complete replacement over a smaller area. However, profitability must also be considered (see below).

10.3.3 Profitability of irrigation

Yield responses are plotted against water deficit (calculated by the IRHO method, as used by most authors) in

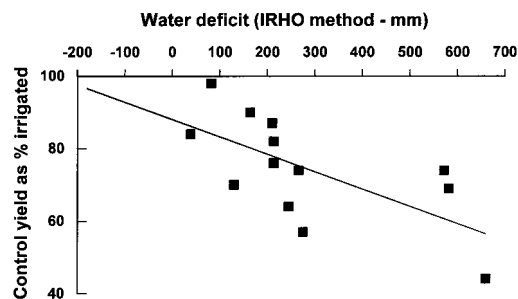


Fig. 10.4 Control yield in irrigation trials as % irrigated yield, in relation to water deficit. IRHO method assumes no effect until AWC exhausted, but regression line here implies some yield loss before deficit starts to accumulate (see also Section 3.2.2.3 and Fig. 10.3) (from data quoted by Corley, 1996).

Fig. 10.4, with unirrigated yields stated as a percentage of irrigated yields. Appreciable responses have been obtained at quite small water deficits (probably because the IRHO method underestimates the degree of stress on shallow soils, and assumes that there is no deficit until 200 mm has been transpired; Section 3.3.2.3). Even with very large deficits, though, responses have not exceeded about 8 t FFB/ha per year. Whether such responses will be profitable depends on local costs and on the palm oil price. Palat *et al.* (2000) considered that furrow or drip irrigation would be profitable in southern Thailand, at all but very low palm oil prices. Lim *et al.* (1994) estimated that flood irrigation on coastal soils in Malaysia would be profitable with very small yield responses, but drip irrigation on an inland soil was unlikely to give sufficient return on investment. Figure 10.4 shows the results of all irrigation experiments. The average percentage response was 36% but the responses in Malaysia were generally small in percentage terms, although the absolute responses were moderate. The largest percentage responses occurred in the Ivory Coast and Colombia.

Comparing different systems, Palat *et al.* (2000) found that the furrow system had the lowest capital cost, but the highest running costs, because of the need for constant maintenance of the furrows. Sprinklers had the highest capital costs, because the water pressure needed was higher than for drip or furrow irrigation. Overall, drip and furrow were equally profitable, with drip preferred because of its simplicity in operation. These authors also showed that, although the yield response per unit water applied was greater if low rates were applied to a large area, full irrigation of a smaller area was more profitable. This was because the capital cost was the same whether low or high rates were applied, and so the larger response per unit area gave the better return.

10.4 FRUIT BUNCH HARVESTING

10.4.1 General

The harvesting operation has a very high priority on a plantation. It is important that all fruits are collected, because any loss of fruit is a direct financial loss. Rapid and clean harvesting also allows the mill to extract the largest possible fraction of the oil and kernels, and maintains the quality of the oil by giving a low level of free fatty acid (FFA).

There has been some change in practices since the early 1980s. Assisted pollination used to be essential to achieve a full fruit set in a bunch in Asian plantations. However, with the introduction of the weevil *Elaidobius kamerunicus* from west Africa (Syed, 1982), natural insect pollination has become adequate throughout the south-east Asian oil palm region, and low fruit set is no longer a major problem (Sections 2.2.2.5, 4.4.7). Despite this, Sugih *et al.* (1996) found that in Riau province in Indonesia the population of the weevils was depressed by heavy rainfall, leading to low fruit set in the wet season from November to January. In the wet season there were only 18 male inflorescences/ha per month, leading to an 88% sex ratio. More weevils were found on 7–9-year-old palms than on 4-year-old palms, probably because the former had more male flowers than the latter. The weevils are more attracted to the male flowers than the female ones, as they eat the pollen, and also lay their eggs on them. In this case, assisted pollination increased the mean bunch weight 5–6 months later, by 20% for young palms and 9% for older ones. Donough *et al.* (1996a) found a similar situation in Sabah, and generally in east Malaysia (Chew Poh Soon, pers. comm.). It may be too early to conclude finally that natural pollination is always sufficient.

10.4.2 Harvesting of young palms

Ablation (the early removal of very small young bunches appearing when the palm first starts to bear) is still used, but it seems to be declining in popularity from the position described by Hartley (1988). The early reasoning behind its use was that the first bunches are small and of poor quality as regards oil/bunch. The individual palms also start fruiting over a period, so the yield is irregular and small, and harvesting is inefficient. The subsequent bunches are larger and have a higher oil/bunch ratio, hence almost the same total oil yield may be gathered more efficiently later, when the cessation of ablation leads to a surge of yield. It seems possible that a desire for tidiness in the young plantation may also make the process attractive, although this

gives no real advantage. Improved vegetative growth is temporary (Chew and Khoo, 1973) and is not required in areas suitable for oil palm. There has been a report (Bénard and Daniel, 1971) that root development was encouraged by ablation, giving greater drought tolerance in a seasonal climate.

Rankine and Fairhurst (1998b) stated that ablation should be carried out for a period of 12–24 months, depending on the precocity of the palms. They also noted that it is usually not done where the palms are in a replanting or the expansion of an existing plantation, and a mill is already operating. This suggests that a major reason for ablation is to delay the need for an expensive mill in new plantations, until the FFB production has reached a reasonable amount for the mill to process, as hinted at by Hartley (1988). Ablation was probably used more when the total area of oil palms in Malaysia was expanding rapidly. Jacquemard (1998) recommended that all female inflorescences should be removed from the palm for some 6 months before normal harvesting was due to start. Young palms of 3 years can now produce quite large yields of bunches, and it is important to get palms into bearing as soon as an economically harvestable yield is formed. Hence, ablation should be of short duration (e.g. 6 months), if used at all, where there are precocious palms and good pollination. Corley and Teo (1976) suggested that partial ablation could be used to maintain monthly bunch numbers below a fixed maximum value, so levelling out the yield as the palms start to fruit more heavily, and avoiding the strongly cyclical yield usually found after ablation stops. This increases the storage of carbohydrate in the trunk, which acts as a reserve and gives a more uniform yield. However, they considered it impractical in Peninsular Malaysia because of the labour shortage.

The cost of harvesting varies widely with the amount of ripe fruit. This depends on the yield productivity/ha and the time between harvesting rounds during which the fruit is ripening. The bunch has to be transported to the road collection point, being carried or placed in a wheelbarrow or on mechanised transport, for a distance that also depends on the density of the road network (see Section 8.2.2). This, in turn, determines the walking distance per tonne of FFB harvested, both along the palm lines and to the road collection point.

The method of harvesting young palms is normally by a chisel on a short handle, which is convenient for gaining access to the peduncle (bunch stalk), even when the subtending leaf is still attached (Plate 10.3). Hartley (1988) pointed out that the frond bases that make harvesting difficult are not those truly subtending



Plate 10.3 Harvesting bunches: a wooden-handled chisel in use on a young palm.

the bunch, but to one side, as the bunch rests on these. The general rule now is to avoid cutting down any green frond unless it is unavoidable. This is particularly important for the young palms, because they have few leaves and a small leaf area index (L) once bearing starts, and it is usually recommended that the next two leaves below the harvested bunch should be allowed to remain if possible.

10.4.3 Harvesting of mature palms

The major difference between young and mature palms is that the latter are taller, which increases the effort of cutting, and makes it more difficult to see ripening bunches and estimate when they are ready for harvesting. Against this, the less dense growth of cover plants makes access easier. From about 5 years onwards it becomes more difficult to cut out the bunch with a chisel, and an alternative tool is used. This is an axe in some areas, but normally a sickle or knife becomes necessary (Plate 10.4). The latter is about 60 cm long, and is mounted on the end of a bamboo or aluminium pole. The possibility of using carbon fibre poles has been considered, but so far none is in routine use. With these, palms of over 12 m tall can be harvested (Lim *et al.*, 1988), although the latest forms of extensible poles can be extended to 16 m. These are normally very effective, and they can increase bunch recovery greatly, with considerable cash



Plate 10.4 Hooked knife attached to the end of a bamboo pole.

savings for old palms (Lim *et al.*, 1988) (Table 10.10). In tall palms it is essential to cut the fronds that subtend the harvested bunch before cutting through the bunch peduncle, to give vision and access. This is acceptable, because the leaf area in old palms is still adequate after a few fronds have been cut off. The handling of the pole is a skilled and heavy job (Plate 10.5).

One of the main objectives of general pruning is to make ripening bunches visible to the harvester when he does his rounds. Once a bunch that is ripe by the current criteria has been missed, it will be very overripe by the time the next harvesting round arrives. There will then be a large number, perhaps 200 or more, of loose fruit scattered on the ground, and the FFA in these

Table 10.10 Data on the use of the long extensible harvesting pole

Palm age (years)	20	21	22	23	24	25	26	27	28	29	30
Palm height (m)	10.5	11.0	11.5	12.0	12.4	12.8	13.2	13.6	14.0	14.4	14.8
Average yield (t/ha per year)	19	18	17	16	15	14.5	14	13.5	13	12	11
Increase recoverable crop (t/ha per year)	2.85	3.06	2.89	3.04	2.85	2.90	2.80	2.97	2.86	3.0	3.3
Increase recoverable crop per harvester (t/year)	77	83	78	82	77	78	76	80	77	81	89

After Lim *et al.* (1988).



Plate 10.5 Harvesting bunches: the hook and pole method for tall palms.

fruits will already be rising. For the same reason, epiphytes on the trunk and old male inflorescences will usually be removed, or collected from the ground if they have fallen off, as the weeded circle is cleared to make the observation and collection of loose fruit easier. There are, however, reasons for leaving the epiphytes, as it has been suggested that they support a beneficial insect population and generally increase biodiversity. When pruning or harvesting is carried out, a considerable number of fronds may be cut off. These should be stacked together in a way that covers the spiny petioles, which otherwise are a danger to the workers, and in a way that minimises erosion.

The use of the knife and pole has been normal in plantations in South-east Asia for many years. In west Africa the harvesting pole has been brought into use, but some wild palms may still be harvested by the harvester climbing up to the ripe bunch and cutting it loose with a machete. Because wild palms only yield reasonably well when their crowns are above any surrounding trees, and are rarely cut down, harvesting may mean climbing up to 20 m or more, using a rope slung around the palm for support.

10.4.4 Harvest round frequency and criteria of ripeness

10.4.4.1 The ripening process

The most important requirement in harvesting is to carry it out at the time when the bunch is ripe. The fruits ripen progressively from the outer and top parts of the bunch. The term 'ripening' can be ambiguous, as applying to oil content, surface colour change or the number of loose fruit of a bunch. The important variable is the oil content. Only the colour change from black to orange (Plate IA) and number of loose fruit can be observed before harvest, and have to be used as an indicator of oil content. The colour change is not sufficiently sensitive, and the last criterion is used in most plantations, as loose fruit per bunch or per kilogram of bunch. In fact, the oil formation and fruit abscission processes are quite separate processes, although almost contemporary, so the exact standard by which 'ripeness' is judged should be clearly defined in all research.

The period over which fruit loosening occurs varies from 11 to 20 days, depending on bunch size. The commercial objective is to determine the best compromise between obtaining the maximum amount of oil in the bunch, and having only a few loose (fully ripe) fruits. This avoids large numbers of loose fruits that have to be picked up and are easily lost (Gan *et al.*, 1994, 1995).

Ripe fruits that are shed from the bunch or remain on its outer surface may be physically damaged because the exocarp becomes softer, so that bruising occurs more easily, liberating an enzyme that de-esterifies the oil and releases FFA (see Section 13.2.3). The lower the amount of acid, the higher will be the quality of the oil. The FFA within a ripening fruit is about 0.5%, and the oil from a bunch that was harvested and milled promptly, at a correct level of ripeness, should have an FFA of around 2%. Currently, 5% FFA is the official limit for premium quality in Malaysia, although a stricter standard will shortly be introduced.

This also means that the harvesting rounds must be reasonably frequent, otherwise there will be many overripe bunches with large numbers of loose fruit, whatever standard is applied. However, there is a pressing shortage of labour in the Malaysian plantation sector (Malek and Mohd Nasir, 1995), so that the frequency of harvesting rounds has risen from 10 to 16 or more days in many estates.

10.4.4.2 Minimum ripeness standards

There has been a lengthy debate about the minimum ripeness standard (MRS) for fruit to be harvested in plantation practice. The only practicable measure is to observe the number of loose fruit, and with palms of any height, that means loose fruit on the ground (Plate IA), because the bunch cannot be examined closely. There will be many more fruit that are technically 'loose', but are still attached to or resting on the bunch (Plate ID). There is extensive evidence that the oil content continues to rise after fruit abscission commences (Corley and Law, 2001). It has been suggested by Rajanaidu *et al.* (1988) that this rise is an artefact caused by the method of measurement, in that the mesocarp loses moisture so that its oil content rises, when it is expressed as a percentage of the total weight. The total weight of the mesocarp decreases as moisture is lost, but the weight of the oil increases after the loss of the first fruit (Corley and Law, 2001).

Gan *et al.* (1995) concluded that the oil/bunch did increase with bunch ripeness, as bunches with 50–200 loose fruits after cutting had oil/bunch 1.9% higher than a bunch with one loose fruit. However, the oil/bunch remained fairly constant for bunches between one and nine loose fruits and those between ten and 50 detached loose fruits, and for practical purposes a bunch might be regarded as ripe if it had one detached fruit. Corley and Law (2001) and Rao *et al.* (2001) examined all the evidence, and both concluded that there was an increase in the bunch oil content after the one-loose-fruit

stage. However, both papers accepted that using a large number of loose fruits as the standard caused practical problems.

The trend now is to take an MRS of one loose fruit per bunch, rather than the earlier standard of two to ten loose fruits per kilogram of bunch weight (Turner and Gillbanks, 1974). This reduces the amount of time that must be spent on fruit collection and the problem of estimating the mean bunch weight. However, the results of Dufrane and Berger (1957) suggested that the relationship of percentage oil to mesocarp is closer with the weight percentage of loose fruit than with the number of loose fruit (Fig. 10.5). It must be borne in mind that, once it starts, the abscission process continues throughout the harvesting interval, so that even if the least ripe bunch harvested on a particular round has only one loose fruit on the ground, the average bunch harvested at that time must have many more. On average, complete detachment of fruit takes less time on small bunches than on large bunches, so harvesting small bunches on time is more critical. However, this lower MRS undoubtedly means that some oil is lost.

Detachment of fruit increases rapidly after the one-loose-fruit stage, and up to 70% of a carrier's time can be spent on collecting loose fruits if the harvesting interval is extended from 10 days to 16 days (Table 10.11) (Gan *et al.*, 1994). The number of loose fruits that are found after the bunch has been harvested and the loose fruits are all detached may be up to ten times as many as those initially seen on the ground, and this delays the cutter greatly (Table 10.11). The time to collect loose fruits with even this one-loose-fruit standard was five times longer than the harvester took to cut the bunch and associated fronds, suggesting that this may be the limiting step in harvesting. The number of loose fruits that were missed and therefore not collected during harvest increased sharply with palm age, presumably because the bunches were larger and fell from a greater height, so scattering larger numbers of fruit over a larger area. With labour shortages as in Malaysia, it may be more cost-effective to set a low loose fruit number as the MRS, even if this means accepting a lower oil/bunch ratio, because the higher standard implies more time spent on picking up loose fruits, and greater losses of these (Rao *et al.*, 2001). The practical problems of applying such standards in the field are discussed by Turner and Gillbanks (1974) and by Rankine and Fairhurst (1998c).

Corley and Law (2001) concluded that the Malaysian industry was losing the equivalent of US\$250 million because of the low oil extraction ratio (OER) that may

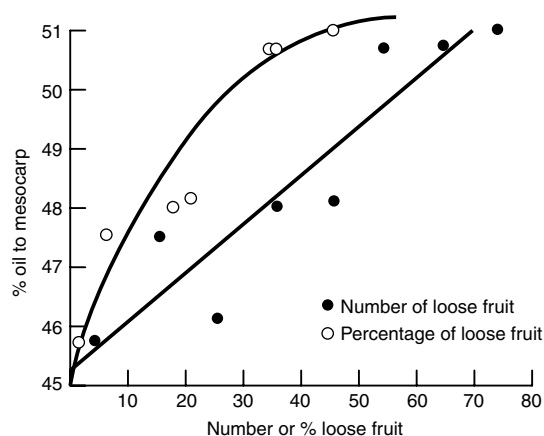


Fig. 10.5 Relationship between percentage oil to mesocarp in oil palm fruit and the number or the percentage of the loose fruits on the bunch (mean weight 4.8 kg). (After Hartley, 1988; after Dufrane and Berger, 1957.)

result from current harvesting standards, and suggested that work on mechanising loose fruit collection in a practical way, to allow a higher standard to be used, should have high priority. A fruit collection machine has been designed, working on the suction principle, but it does not appear to have been adopted in practice (Ahmad Hitam and Ahmad Zamri, 2000). There is no doubt that mills in Indonesia processing fruit from young plantations are obtaining OERs of up to 24%, whereas most Malaysian mills now have OERs around 20%, with substantially the same type of planting material (see Section 10.5.2).

10.4.5 Transportation in-field and to the mill

Transportation to the road has always been a problem in harvesting, because the crop is dispersed over a large area. This problem depends very much on the road density in the plantation, because the productivity of any carrier, person, animal or machine, will vary directly with the road density. The problem is more difficult in hilly country, where the road density needs to be even higher. Clendon (1990) found that, at that time, harvesting and collection of FFB comprised half the total labour expenditure on the estates. Stringfellow (1999) found even higher values (Table 10.8). The weight of individual bunches, the frequent roughness of terrain and the incompleteness of cover control can make this a heavy task. Now that mechanisation is becoming more fully accepted, these problems should be soluble. The

Table 10.11 Time and motion studies on harvesting and collection of bunches by a cutter/carrier team in 14-year-old palms on a coastal estate in Malaysia, using MRS mean between one and ten loose fruit

	Harvesting interval							
	10 days		12 days		14 days		16 days	
	% ^b	s/palm	% ^b	s/palm	% ^b	s/palm	% ^b	s/palm
<i>Cutter</i>								
Walking ^a	45	39	30	20	23	21	16	14
Adjusting poles	–	–	1	1	1	1	1	1
Cutting fronds	21	18	24	16	31	28	32	28
Stacking fronds	15	13	27	18	26	23	29	25
Cutting bunches	19	16	18	12	19	17	22	19
Total	100	86	100	67	100	90	100	87
<i>Carrier</i>								
Walking	27	33	22	27	26	43	13	26
Trim stalk	2	2	5	6	3	5	2	5
Load bunches on wheelbarrow	6	7	7	9	7	11	16	13
Collect/load loose fruits	56	68	56	68	51	84	71	146
Transport to platform	9	12	10	11	13	21	8	16
Total	100	122	100	121	100	164	100	206
<i>Time in motion (h)</i>								
Cutter	1.58	2.10	3.08	3.92				
Carrier	3.13	3.79	4.55	9.36				

^aWalking between harvested palms.^bPercentage of total time.After Gan *et al.* (1994).

first improvement in transport was to use a net, into which all bunches were loaded before being hoisted into the collection lorry or trailer by a small hydraulic crane attached to the lorry or tractor (Plate 10.6). The nets are set out at the roadside collection points, and bunches brought to this point are placed in them. This method is still widely used. The workers (carriers or cutters) used bicycles or wheelbarrows to carry the fruit to the collection point, and in many cases still do so; for example, Rankine and Fairhurst (1998c) recommend issuing the workers with wheelbarrows. Sometimes animal transport is used (Plates 10.7, 10.8, VA), such as buffaloes (Wan, 1973) or bullocks in Asia or mules in America, where the well-known obstinacy of the latter can cause considerable problems (Hartley, 1988). A bullock-cart can transport some 1.5 t of bunches to the roadside. Bullocks are reported to cause puddling of the ground, but less so than wheeled transport. They are consequently favoured in some areas of high rainfall where there is a high water table. Dahlan *et al.* (1997) calculated the relationship between buffalo weight and pulling power, and considered them to have great potential. In Indonesia and some other oil palm countries the cost of labour is still low

enough for estates to find that manual transport of bunches to the roadside is the cheapest method.

In Malaysia various mechanised systems have been under test since the 1980s and have gradually been developed (Malek and Yaakob Hitam, 1989) (Fig. 10.6). Fawzi (1994) recommended a low-powered 'mechanical buffalo' for collecting FFB on terraces, producing higher labour productivity. Kamarudzaman *et al.* (1994) studied the introduction of a mechanised system of minitractors with mechanical loading, finding that two workers could be omitted for each unit deployed, and that the harvesters' output increased by 65%. Each unit could deal with about 230–250 ha of mature palms. At that time, there was little cost saving overall, and the use of a hydraulically operated grab for loading was found to be more expensive than manual labour, so this was clearly a little before its time. Hartley (1988, p. 462) thought that mechanised systems in general were not cost-effective at that time. This has now changed, and the present situation on the mechanisation of in-field transport is discussed in Section 10.4.6. As labour shortages escalated, a saving on labour became attractive even if the cash saving was quite small. The problems of

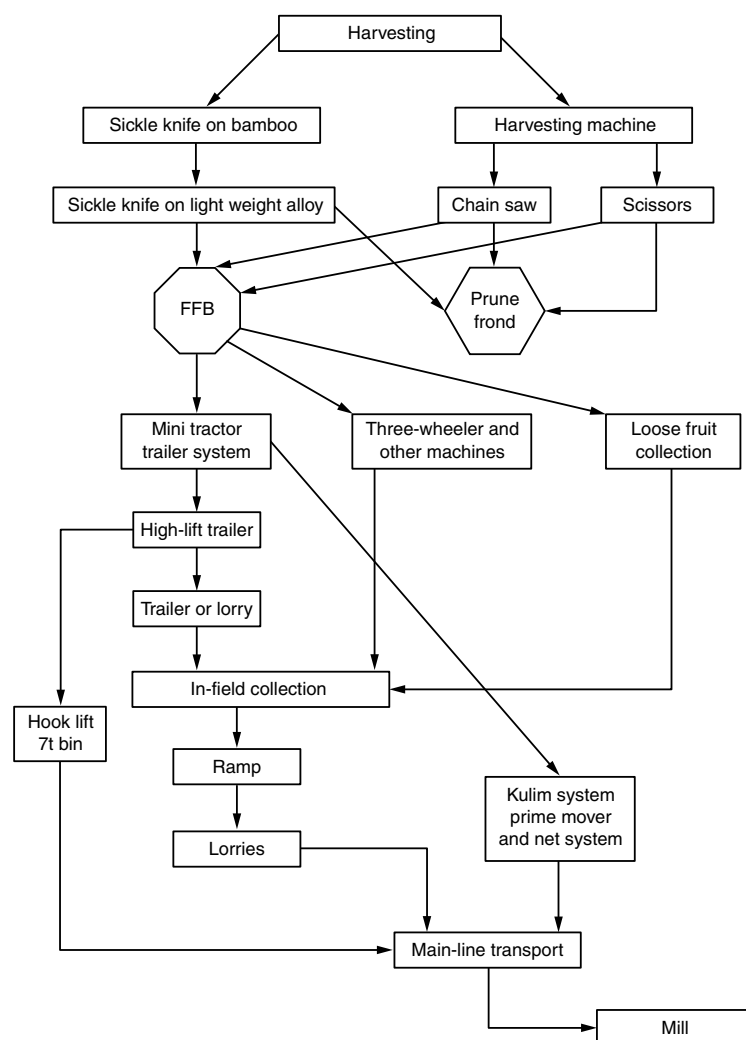


Fig. 10.6 Schematic diagram of the various steps and alternatives in harvesting, infield collection and main-line collection of FFB. (After Ahmad Hitam and Ahmad Zamri, 2000.)

wet, uneven and irregular ground still remain in some estates, where the use of wheeled transport remains difficult. In such circumstances the use of buffaloes is probably the best option (Plate VA).

For further transport to the mill a tractor or a lorry can be used, but if the distance is long, a tractor is not practical. A hook-lift unit is essential for lifting the FFB into the lorry, fitted either on the tractor or on the lorry chassis (Plate 10.6) with the FFB placed in a net. It is now becoming more common for it to be collected by a high-lift trailer in the field and emptied into a container (bin) at the collection point (Plate VB). This is subsequently lifted or pulled onto the lorry or flat-bed trailer by a hook-lift unit (Kamarudzaman, 2000). Where a rail system is used the steel cages in which the

fruit is collected go straight into the steriliser (Plate 10.8). These cages can also be used with low-loading trailers and tractors. The early developments in this area can be found in Hartley (1988, pp. 461–464).

10.4.6 Mechanisation of collection and in-field transport of fresh fruit bunches

The difficult part of fruit collection has always been the distance from the palm to the road, and the provision of minitractors and lifting trailers with a grabber has made a great difference, and allowed considerable labour savings (Chew *et al.*, 1996; de Souza, 2000) (Table 10.12). There is a clear incentive to mechanise because of the shortage of labour, but it is also important that it shall



Plate 10.6 Lifting bunches from the roadside in nets by tractor-mounted crane in the so-called 'Kulim system' of bunch collection and transport.



Plate 10.7 Bunches carried out of the fields on mules in Ecuador.



Plate 10.8 Harvest collection from field to railside by bullock cart on a coastal estate in Malaysia. (T. Menendez.)

Table 10.12 Capital and operating costs of in-field transportation and collecting machines

Machine	Capital costs (RM)	Productivity (t FFB/day)	Operation costs (RM) (less operator)
Minitractor with trailer	32,000	15–23	1.30
Grabber	48,000	18–28	1.40
Grabber with high-lift trailer	52,000	18–28	1.45
Super crawler	52,000	15–23	1.30
Taltrac	32,000	18–28	1.10
Rambo with grabber	52,000	18–28	1.20
Wakfoot	37,000	18–23	1.20
Badang	12,000	12–14	0.90
Iron horse	12,000	12–14	0.90
Power cart	10,000	13–15	0.90
Wheelbarrow	80	0.9–1.4	ns

After Ahmad Hitam and Ahmad Zamri (2000).

Table 10.13 Performance per worker of mechanical in-field transporter for bunches

System	Av. daily output (t)	Workers per mech. team	Output per harvester (t/day)	No. of harvesters	Total workers	Workers reduction	Area/day (ha)
Manual	22	–	1.47	15	15	–	20–23
Minitractor (manual loading)	24	3	9.00	12	3	3	25–30
Minitractor (Grabber)	22	1	2.44	9	10	5	25–30
Super crawler	20	3	2.22	9	12	3	20–25
Rambo	18	3	2.25	8	11	4	20–22
Taltrac	20	3	2.22	9	12	3	22–23
Wakfoot	20	3	2.22	9	12	3	20–22
Mech. buffalo/Iron horse/Wu cart	10	5	2.10	5 ^a	5	5 ^b	14–15

^aThe operators are harvesters.

^bEquivalent to.

After Ahmad Hitam and Ahmad Zamri (2000).

at least break even in economic terms. Kamarudzaman and Lani Rosdi (1996) found a saving of 7–10% with the introduction of minitractors. Ooi and Sim (1997) estimated savings from mechanising the FFB evacuation and fertiliser application: mechanising FFB in-field transport reduced labour requirement by 54% and cost by 22%. There was a further saving in that the density of the road network could be reduced from 75 m/ha on flat land to 22 m/ha because of the greater carrying capacity from palm row to road. The authors recommended a mean density of 40 m/ha to allow for fields with some hilly land.

Kamarudzaman (2000) reviewed recent initiatives on this subject. Loading was far more rapid with the integrated FFB evacuation system than with nets or manual loading. The complete system with a minitractor,

grabber (a hydraulic grab that loads the bunches (Plate VC)) and high-lift trailer appears to be very practicable. The high-lift trailer is particularly useful because it loads the bunches directly into the lorry without further manual handling (Kamarudzaman, 2000, Plate VB). The capital expenditure was lower than other systems, and over all there was a saving of RM 3.50/t FFB. Ahmad Hitam and Ahmad Zamri (2000) presented a large number of photographs showing these various stages in mechanisation, and the various vehicles that have been introduced and tested, together with an overview of the subject. They made no definite recommendation for any of these machines, but the performance of these vehicles is analysed in Table 10.13 (Ahmad Hitam and Ahmad Zamri, 2000). On average, the reduction in the number of workers is

Table 10.14 Performance of transporters in the field with respect to output and operating cost

Type of transport	Output (t/day)	Operating cost (RM/h)
Wheelbarrow	2–3	Negligible
Buffalo cart	4–6	Negligible
Mechanical buffalo	6–8	1.25–1.75
Iron horse	10–12	1.50–2.50
Crawler dumper	12–20	3.00–4.00
Minitractor	18–28	2.00–3.00

After Summugam (2000).

about 20–33%; the question is whether this gain compensates for the capital and running expenses of the vehicle. A comparison of the work rate in all of these systems is given by Summugam (2000) (Table 10.14). A mechanised system can include a vacuum loose fruit collector, including a separator to produce clean fruit, but this is only claimed to be ‘above 80%’ effective, which suggests that a great deal of debris will be sent to the mill unless there is also some manual cleaning. There are other more exotic transport systems, including the Sawit overhead cable system for bringing down bunches from steep palm fields (Hoong, H.W. 2000).

A comparable mechanised system was reported by Graham and Soupa (2000) in Papua New Guinea (PNG). This comprises a tractor and scissor-lift trailer in the field, feeding into 15 t bins for transport to the mill, and it has been successful, once various problems had been solved. They noted that the skilled harvesters are now much more effective because this integrated system frees them to concentrate on their main task of cutting fronds and bunches.

It has been argued above that all management and staff should be committed to mechanisation because they understand the gains in profitability. This often does not happen at present because of the problems that senior management perceive with staff and unions. Mechanisation is not a one-off brief change in the routine of the plantation. It must be an ongoing and continuing change, which gradually permeates and modernises all functions within the plantation, and Summugam (2000) discussed some of the administrative and technical implications. He argued that all staff, up to the chairperson or owner, should be involved in the operation. Good training in the new techniques should gradually bring acceptance. Other changes may also be needed including new objectives for oil palm breeding programmes (Sitepu *et al.*, 2002).

It is likely that plantations will have to spend more time and resources on training their staff. In all aspects of oil palm culture and use the need for better control and precision is increasing (Chew, 1998; Mahbob and Abdullah, 2001), and this can only be obtained with more expert and trained staff. Without this, maximum profits cannot be made.

10.4.7 Need for a harvesting machine

Harvesting oil palms is a difficult and expensive task, especially compared with the ease and cheapness of combine-harvesting arable crops (Tinker, 2000a). Any progress in saving large labour cost has been assumed to demand a harvesting machine, but the heavy labour cost of picking up loose fruit may be more important. Studies on the work rate of harvesting (Gan *et al.*, 1995) showed that harvesters (or carriers) were spending much more time on collecting loose fruit than in actually cutting down bunches. In any case, the progress towards a harvesting machine so far has been meagre and unpromising (Ahmad Hitam and Ahmad Zamri, 2000). Experimental machines have been slow and cumbersome, and simple inspection does not give any confidence that most of these machines could carry out the rapid manoeuvring needed. Early prototypes aimed to lift the harvester up to the fruit, whereas later ones have aimed to use a mechanical cutter controlled from the ground. The need to approach the palm from all sides is a difficult problem. Hartley (1988) noted that in Honduras and Costa Rica vehicles with booms capable of lifting harvesters up into palm crowns were being used prior to 1973 (Washburn, 1973). It must be assumed that these were eventually found to be non-viable.

However, it is scarcely possible that a machine can be designed to move rapidly from palm to palm and around the palms unless the levelling of oil palm fields is done much more carefully than it is now. Only on certain coastal estates is a level surface produced that bears any resemblance to the levelled land on which precision agriculture is being developed in temperate countries. This applies both to machines for harvesting bunches and to those for picking up loose fruit. It seems likely that estates will have to commit themselves more wholeheartedly to preparation for mechanisation, accepting that a much better standard of land levelling is needed. As part of the way towards that, Ahmad Hitam and Ahmad Zamri (2000) stated that a 3 m wide machine roadway is needed along every second interline to allow general mechanisation, using the alternate one to the frond-stacking interlines. Hartley (1988, p. 439) records this as being in use in some coastal estates. A tracked

vehicle is better for rough or wet land (Ahmad Hitam and Ahmad Zamri, 1996), and has lower ground pressure than wheeled vehicles, but it is more expensive.

Sloping areas above 6° slope are very difficult to mechanise. It seems unlikely that any of the experimental harvesting machines tested so far could work on significant slopes or on irregular surfaces. However, the success of other mechanisation projects (Ahmad Hitam and Ahmad Zamri, 2000) does give some confidence that ultimately a usable machine will be developed for level land. It is worth repeating (Tinker, 2000a) that a machine such as the combine harvester, which is the basis of the success of arable oil and cereal crops, was developed over a period of many decades, and only gradually became used everywhere. It is perhaps expecting too much to hope that a successful oil palm harvesting machine will suddenly appear, even though the mechanical resources available are so much greater now than when the combine was being developed.

It is notable that an authoritative text on agricultural engineering (ICAE, 1999) does not mention oil palms except for a 'special knife' used in harvesting. Unless the need for harvesting machinery is made more explicit, insufficient attention will be paid to it by agricultural engineers outside the immediate oil palm industry. Russell (2000) stated that steep terrain had defeated many attempts at mechanisation in different crops, and that in general steep slopes should be left to forestry. However, he considered that the problem of a harvesting machine for reasonably level land should be soluble. Russell suggested that the problem should be given to practical field-orientated engineers who had experience of designing new working machines. It may be that such an approach would overcome the poor record of development in the oil palm countries themselves (Nielsen, 1999).

There is a view that these problems will not be solved with the palm structure as it is at present, and that radical changes to the palm architecture are needed. To select for novel characteristics, for a machine which is as yet unknown, is clearly a difficult business, and progress can only be stepwise (Mahmud, 2000). There are, however, certain characteristics that are valuable for harvesting both by current manual methods and by any machine generally similar to those now being tested. Many breeding organisations have aimed at breeding palms with a smaller annual extension rate, and there has been some success in this (see Section 5.3.4.2). CIRAD has had a programme aimed at a smaller extension rate, and also at larger bunch weight (to reduce the number of individual bunches to harvest) and changing the length and circumference of the bunch stalk

(to make it easier to reach and to cut). They also aimed to make cutting the subtending leaf easier, by decreasing the petiole cross-section, and increasing the length of the petiole and rachis, to increase the angle between the frond and the vertical. An examination of these spatial characteristics in planting material (Le Guen *et al.*, 1991) found that there was large variability in all of them. They concluded that the characteristics that are of greatest utility in harvesting are the bunch stalk length and thickness, the cross-section and angle to the vertical of the fronds, and the height of the palms. These points seem to be generally accepted, but it is not clear what progress has been made yet. However, Sitepu *et al.* (2002) suggested that breeding might have to aim for smaller bunch weights, because the need to lift large bunches in mechanised harvesting would mean that the machinery would be so heavy that soil compaction might occur.

Wakefield (1981) made a theoretical study of the acceptable cost of a harvesting machine, but the data are well out of date by now, and the exercise needs to be repeated. In the current Malaysian conditions of labour shortage, it is essential to move labour from other tasks into harvesting by mechanising more where this is practicable now.

10.5 THE OIL EXTRACTION RATIO PROBLEM

10.5.1 Factors affecting the oil extraction ratio

It is important to distinguish between the OER and the inherent oil/bunch (O/B) ratio of a palm, or even of a single bunch. The latter depend on the palm and environmental characteristics, such as soil, rainfall, planting material, palm age, weevil population, pollen density and all the various agronomic practices used (Ho *et al.*, 1996). The O/B is determined on a bunch in a laboratory-style operation, but there are many small differences in the detailed methods, and few results are strictly comparable with those of other laboratories (Rajanaidu *et al.*, 1985) (see Section 5.2.4). The OER is determined on actual oil production by some form of mill, and this therefore depends on the inherent O/B, and also on harvesting standards and practices on the plantation, and efficiency at the mill. It is assumed that the mean O/B measured on the bunches taken into a mill will be roughly proportional to the OER, but the numbers will not be the same. The amount of oil produced during a given period is the weight of FFB

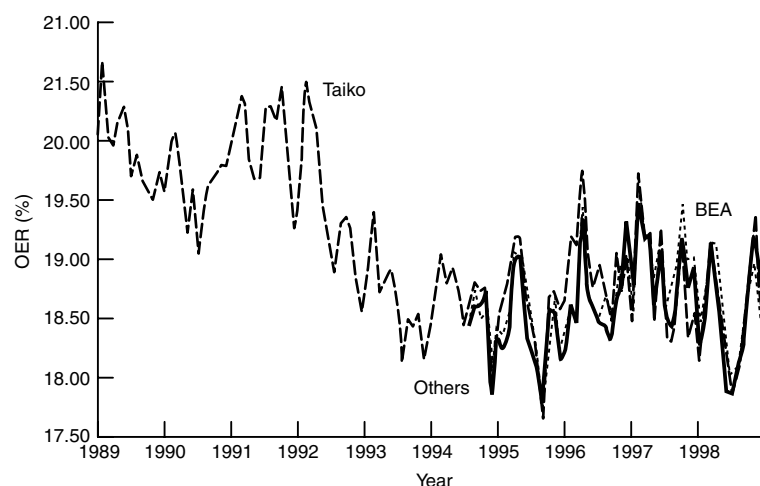


Fig. 10.7 Examples of measured oil extraction ratio from mills in Peninsular Malaysia between 1989 and 1999, from the Taiko and Boustead (BEA) plantations. (After *Applied Agricultural Review*, Jan. 1999.)

dealt with by the mill, multiplied by the OER. This last value is consequently of the highest importance, and is a critical measure both of the efficiency of the field plantation, in producing FFB with a high O/B ratio and harvesting it efficiently, and of the efficiency of the plantation mill.

10.5.2 Decline in oil extraction ratio in Peninsular Malaysia

Over the past decade (roughly since 1991/1992), OER in Peninsular Malaysia has declined by more than 1%, so that over 5% of the oil expected is not recovered (Fig. 10.7). This may now be happening in Sabah also, but as yet there seems to be no analogous effect in Indonesia or other countries. Nevertheless, this effect is of world-wide concern, because Malaysia is at present the most developed and the most efficient palm oil producer, and the causes of this problem may appear elsewhere as their stage of development moves forward. Corley and Law (2001) concluded that the Malaysian industry was losing US\$250 million per year because of the low OER, probably owing to the current harvesting standards and procedures, and suggested that the mechanisation of loose fruit collection should have very high priority. The causes are debatable, but mills in Indonesia, processing fruit from young plantations, are obtaining OERs of around 24% (Foster, 2002; pers. comm.), whereas 20% is now regarded as normal in Malaysia. The apparent financial loss has caused intense concern, and much study to understand and reverse the change (Ariffin and Jalani, 1994). Up to the time of writing there has been no clear decision on the cause(s),

and most explanations are convincing in only a minority of plantations. Researchers on the subject have studied each proposed cause in turn, and the suggested causes are as follows:

- low standards of harvesting: long intervals between harvesting rounds, harvesting of underripe fruit by harvesting too early, or loss of loose high-oil-containing fruit because harvesting is too late and is careless. It is believed that this occurs because of the grave labour shortage in the industry, or because of failures in management, and has tended to be the preferred explanation (Ariffin and Jalani, 1994);
- failures in the mills (Menon, 2000): but there is no evidence that mill efficiency has declined over this period;
- contamination of the *tenera* seed with *dura* material because of faulty pollination of the seed palm bunches. Rao *et al.* (1994) estimated that this effect was real, but too small to account for a substantial part of the change in OER;
- palm age: replanting has not been done as soon as is desirable, and the mean age of the palm population is increasing (Table 10.15) (Jalani *et al.*, 2001). If the oil/bunch on large bunches from old palms is lower than that of smaller bunches from the same palms when they were younger, then there should be an effect of palm age. However, young palms may have the advantage of 10–15 years of breeding for high oil/bunch in such a comparison, which may give a specious impression of a decline in OER with the age of the palm;
- climatic changes: El Niño or haze from the eruption of Mount Pinatubo has been suggested, but neither of

Table 10.15 The age profile of palms in six groupings, by percentage of total planted area

Period	Mean total area (ha)	Age groupings (years) (% by ha)					
		1–3	4–8	9–13	14–18	19–24	≥25
1975–1979	786,009	33.52	42.30	14.73	8.29	1.16	0.1
1980–1984	1,179,454	22.21	40.10	21.55	9.85	6.29	0
1985–1989	1,701,413	16.23	35.72	24.42	14.93	7.30	1.40
1990–1994	2,207,815	12.84	34.12	19.77	18.70	13.05	1.50
1995–1999	2,903,394	13.36	30.04	21.42	15.07	16.87	3.24
2000	3,374,485	15.39	28.89	17.22	16.92	13.81	7.77

After Jalani *et al.* (2001). Bold point indicates largest value in an age class.

Table 10.16 Relationship between loose fruit numbers, harvesting interval, state of bunches and oil extraction ratio

Financial year	Harvesting interval (days)	Loose fruits per bunch (no.)	Unripe (%)	Overripe (%)	Rotten (%)	Observed OER (%)
1986/87	12.1	2.3	–	–	–	20.17
1987/88	–	3.9	–	–	–	19.65
1988/89	–	18.5	9.0	9.6	1.3	19.95
1989/90	13.4	31.6	13.7	9.1	1.9	19.73
1990/91	–	32.0	11.2	10.0	2.6	19.50
1991/92	–	29.7	11.3	11.5	2.1	19.20
1992/93	13.8	18.8	9.3	12.4	1.9	19.13
1993/94	–	26.3	8.0	13.5	1.5	18.63
1994/95	11.2	17.3	4.3	14.7	1.0	19.05
1995/96	–	16.0	4.1	17.0	0.9	18.99
Correlation with OER	0.04ns	–0.38ns	0.55ns	–0.78*	0.27ns	

After Ho *et al.* (1996).

*p – <0.05; ns: not significant.

these, nor any other climatic effect can explain the OER change. None appears sufficiently consistent to explain an effect that has lasted for a decade, although there may be a relation between OER and radiation and haze (Caliman and Southworth, 1998). The mean effect of haze was to reduce OER by 2 percentage points, and to reduce the FFB by 1.3 t/ha in one factory, according to the SIMPALM model. It seems that low OER occurs in sharp isolated bursts in Indonesia, and the pattern is thus very different from the steady decrease and continued low value of OER in Malaysia. There is an accepted effect of rainfall and season on OER, with both very high and very low rainfall depressing OER, but there is no reason why this should cause the observed long-term trend. Other countries such as PNG and Costa Rica (Peralta *et al.*, 1998) have not experienced such problems, so widespread changes such as the introduction of the weevil cannot be blamed.

Several plantation groups have studied this problem, using the resources of their palm fields. Ho *et al.* (1996) studied harvesting standards at Sime Darby. Table 10.16 shows the general declining trend in OER, but the expected correlations with various factors were not found. Unripe and rotten bunches were positively correlated with OER, whereas overripe bunches were negatively correlated. The authors concluded that harvesting standards as such were not the immediate cause of the general OER trend. *Dura* contamination of the FFB increased sharply with the introduction of the weevil about 1982, but was declining again by 1989. It was calculated that with a mean *dura* contamination of 3.08% in 1993/94 the effect on OER would only be 0.15% loss. The measured oil/bunch was clearly smaller in older palms (Table 10.17) over the planting year range 1968–1989, but this was not a proper comparison, as the planting material changed, as pointed out above. The lowest practical harvesting standard is the one-loose-fruit standard (Section 10.4.4). This has been

Table 10.17 Age distribution of fields in a plantation, and their FFB production: (OER) predicted was calculated from the known trend of OER with age in Fig. 10.10 (after Ho *et al.* (1996).

Financial year		Year in harvesting						OER predicted (%)	OER observed (%)	Outside crop (%)
		1–5	6–10	11–15	16–20	21–25	>26			
86/87	(a)	5.93	18.63	30.87	32.07	11.67	0.82	21.56	20.17	13.7
	(b)	12.16	23.01	31.02	29.29	4.32	0.21			
	(c)	2.868	5.247	6.726	5.894	0.788	0.034			
88/89	(a)	5.51	15.23	25.24	29.98	21.95	2.08	21.19	19.95	19.5
	(b)	7.50	21.04	33.00	30.93	7.35	0.18			
	(c)	1.752	4.816	7.117	6.128	1.346	0.030			
90/91	(a)	13.50	9.67	17.82	28.74	28.46	1.79	20.97	19.50	15.5
	(b)	11.72	17.10	26.45	28.48	15.77	0.49			
	(c)	2.732	3.896	5.686	5.676	2.900	0.080			
93/94	(a)	12.05	16.28	14.35	23.17	26.91	7.24	20.92	18.63	32.0
	(b)	17.80	13.46	20.21	29.28	18.64	0.60			
	(c)	4.177	3.096	4.371	5.819	3.360	0.101			

Note: (a) Age distribution (%) of mature palms.

(b) Production distribution (%) for different age groups.

(c) Contribution towards overall OER by respective age groups using modified regression equation by Wood *et al.* (1987).

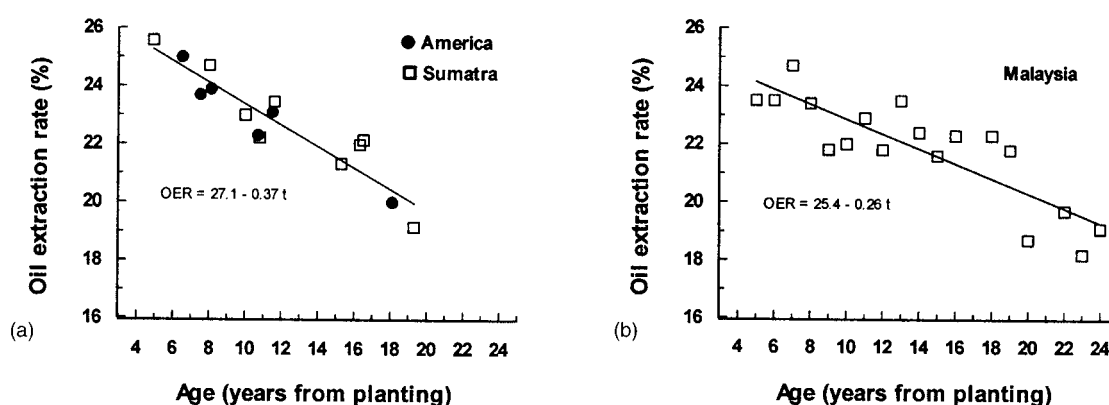


Fig. 10.8 Relationship of oil extraction rate with palm age in different regions. (a) Annual mean mill extraction rates from Colombia and Costa Rica (from Peralta *et al.*, 1998 and García Nuñez *et al.*, 1998), and Sumatra (H.L. Foster, unpubl.). Age is average age of all plantings feeding into each mill. The regression line is fitted to all data points. (b) Extraction rates from a milling study, in which fruit from individual planting years were processed as separate batches. (Redrawn from Ho *et al.*, 1996 from original data of Wood (unpublished)).

reported not to decrease the OER (Wood *et al.*, 1985a, b; Ho *et al.*, 1996), but there are other differing views (see Section 10.4.4.2).

During this period and these studies, there has always been an inverse correlation between oil/bunch and kernel/bunch. Large bunches from old palms now have a high fruit set because of the weevil, and the amount of less ripe inner fruit causes a negative correlation between age of palm and OER (Fig. 10.8 and see figure legend)

(Ho *et al.*, 1996), because unripe fruit have low oil/fruit, but reasonable kernel/fruit. The trend of decreasing OER with age is quite clear on both (a) and (b) graphs, and quite similar for both data sets. The OER values in Fig. 10.8b are from a Sime Darby milling study, with fruit harvested under rigorously controlled conditions. The values in Fig. 10.8a are from a set of commercial mills in different countries, with differing climates, so the close agreement is surprising. Some of

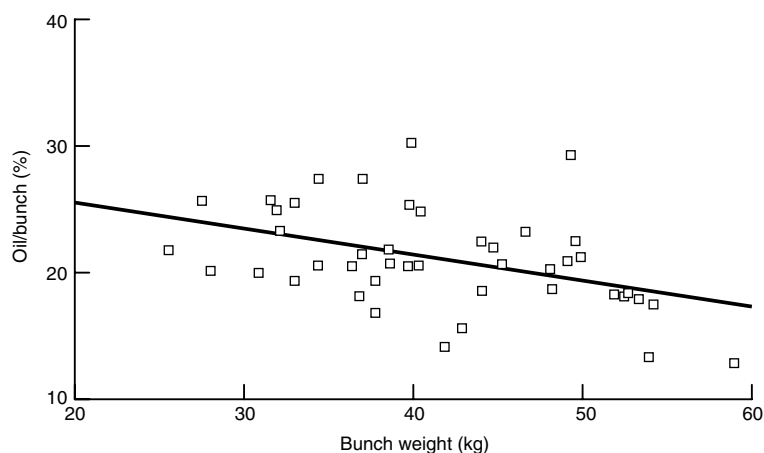


Fig. 10.9 Relationship between bunch weight and content of oil/bunch. (After *Applied Agricultural Review*, Jan. 1999, AAR Internal Report.)

these mills were getting over 22% OER, showing what can be obtained in commercial practice.

The Sime Darby plantations in Sabah tended to have low fruit set, blamed largely on heavy rainfall; this was probably the cause of depressed OER within the September–January period. Low rainfall depressed OER 2 months and 11 months later. The net conclusion was that harvesting standards did not alter OER significantly, and that the most likely cause was the age of the palms, although this could only account for 40% of the decline (Ho *et al.*, 1996). There is an accepted effect of rainfall and of season on OER, with both very high and very low rainfall depressing OER, but there is no reason why this should cause the observed long-term changes.

The effect of fertilisers on OER has been studied in Malaysia by Foster *et al.* (1988b) and in Indonesia by Prabowo and Foster (1998). Phosphorus, potassium and magnesium were found to affect bunch components, whereas nitrogen had no effect. The individual effects of phosphorus also cancelled out, so that it did not affect oil/bunch or OER. Magnesium slightly increased oil/bunch. However, potassium decreased oil/bunch significantly in two out of six trials, on inland soils, but increased it slightly on coastal soils. Both effects occurred while potassium was causing a significant increase in oil yield. Potassium also increased the kernel/bunch significantly in three of the trials; the opposite effect on oil and on kernels is the same as is found in other circumstances discussed above. However, the rates of potassium fertiliser applied have not increased sufficiently in the past decade for this effect to explain any important part of the OER changes in Malaysia. It has been suggested (Prabowo and Foster, 1998; Rao *et al.*, 2001) that the potassium effect is due to the increase in

the moisture content of the fruit, such as happens in other species (see Section 11.4.6). In studies on different soil types, the OER differences found between palms on coastal soils (Sungei Buloh series) and inland soils (Rengam and Kulai series) were very small and non-significant.

Figure 10.8 suggests that the relation of OER and palm age is remarkably similar in different oil palm-growing countries. From these straight-line relationships the expected OER for any mean palm age can be predicted. The average age of Malaysian estate oil palms in 2000 was 13.4 years (Jalani *et al.*, 2001). The two regression lines in Fig. 10.8 indicate OER values of 22.1 and 21.9 respectively, whereas the actual Malaysian national average OER at this date was 18.9% (Jalani *et al.*, 2001). It therefore appears that Malaysia is ‘losing’ around 3% OER, or 15% of its potential production, even after allowing for the mean age of its palms. This suggests that simply increasing the rate of replanting will not solve this problem.

10.5.3 Possible solutions

There are many publications on this subject, and here a summary only is given. Chew (1996) has given a broader discussion. There appears to be no doubt that older palms with larger bunches give both lower oil/bunch and lower OER, as tested now (Figs 10.8–10.10). However, this is comparing palms of different genetic material. In any case, Ho *et al.* (1996) concluded that the measured differences in bunch size only accounted for part of the loss of OER. There is certainly an effect of harvesting practices, and the oil content of the fruit continues to increase beyond the one-loose-fruit stage, but most of the fruit harvested with this MRS will in fact

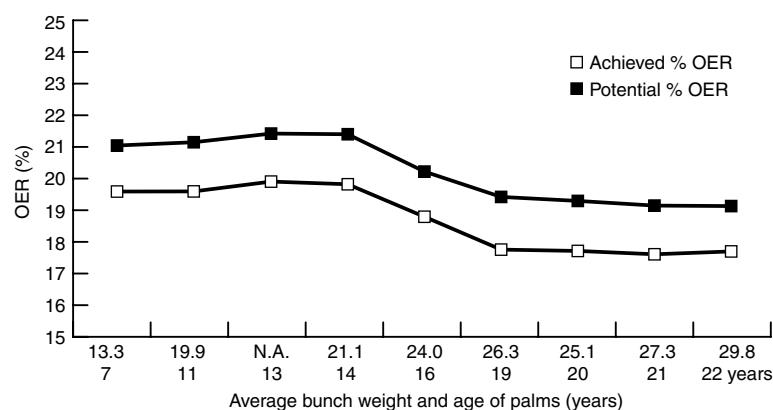


Fig. 10.10 Relationship between measured and potential oil extraction rate values for mill tests on one estate and the average bunch weight, with palm age noted on the same axis. (After Sharma 1998.)

Table 10.18a Immature and total planting areas, new planting of areas under any vegetation other than oil palms, replanting of areas under oil palms, annual rates of replanting and new planting over replanting

Period	Mean total planting (ha)	Immature		New planting ^a (%)	Replanting(%) (%)	Annual rates of replanting (%)	% New over replanting
		(ha)	(%)				
1975–1979	786,009	259,100	32.96	9.44	23.51	7.84	40.15
1980–1984	1,179,454	259,958	22.04	6.68	15.35	5.12	43.51
1984–1989	1,701,413	273,865	16.09	7.24	8.85	2.95	81.81
1990–1994	2,207,394	282,378	12.79	4.22	8.56	2.85	49.30
1995–1999	2,903,394	390,785	13.46	6.21	7.25	2.41	85.66

^a Any area not previously under oil palms.
After Jalani *et al.* (2001).

be considerably riper. With very careless harvesting many 'black bunches' may be harvested, which will certainly lower OER substantially (Rao *et al.*, 2001). It is very difficult to be certain of the magnitude of the effect in practice, and the debate over ripeness at harvesting continues. The increased fruit set in the inner part of the bunch resulting from the introduction of the weevil certainly has increased the fraction of inner fruit, which tends to be less ripe for any given ripeness standard applicable to the external fruit (Plate IIB). However, the weevil was introduced well before the OER decline was noticed, so it is difficult to argue that the decline was caused by the weevil introduction. In any case, no similar effect has been noticed in other countries into which the weevil was introduced.

Rao *et al.* (2001) showed that differences in mill efficiency caused significant differences in OER, but there is no evidence of a general decrease in mill efficiency.

The question remains: what is to be done? There is an apparent effect of large bunches from old palms. If this is the cause the cure is an accelerated replanting programme throughout Peninsular Malaysia with

Table 10.18b Age profile of Malaysian oil palm

Age profile	% of planted area	
	1999	2000*
1–3 years	13.78	15.39
4–8 years	30.82	28.89
9–13 years	18.98	17.22
14–18 years	15.65	16.92
19–24 years	13.81	13.81
25 years and above	6.96	7.77
Total planted area (ha)	3,313,393	3,374,485

Source: MPOA.

* Estimated.

new material, preferably clonal, with an increased oil/bunch ratio. It is claimed that replanting and new planting has decreased in percentage terms in recent years (Jalani *et al.*, 2001), so that the mean age of the palms has increased (Table 10.18a, b). This is correct, but it is to be expected under Malaysian circumstances

(Section 10.6.2), and it is difficult to see how the general demands for more replanting are justified. If it is agreed that the age effect on OER is real, it simply means that there is a greater economic reason to invest in new palms.

No factors that are part of the harvesting process can be ignored. These include observing agreed standards, keeping the intervals between rounds reasonably short, collecting all loose fruit, and no harvesting of any under-ripe fruit. Careless harvesting may cause a considerable loss of oil by harvesting underripe or overripe bunches, the latter causing large losses of loose fruit. Rao *et al.* (2001) considered the whole problem at length and gave lists of possible causes, but they could not identify any one overriding cause.

10.6 PALM AGE, REPLANTING AND NATIONAL YIELD

10.6.1 Palm age problems and the need for replanting

As the palms in a field age, various problems appear. First, the most obvious one is in harvesting, with the difficulty of inspecting bunches and assessing ripeness, and in cutting interfering fronds and the bunch stalk itself. The distance of falling may lead to greater bruising injury of the external fruit. Secondly, there is the decrease in OER with palm age, possibly associated with the increasing size of bunch, and a lower mean degree of ripeness (Section 10.5.3). Thirdly, if planting material is being progressively improved with time, larger yields should be obtainable by replanting with the new material. This issue will be particularly important as clonal material with very high oil/bunch ratio becomes accepted.

There is no obvious age at which a field must be replanted, and it is a matter for managerial judgement, which may be affected by the price of oil or the labour situation on the estate. The consensus judgement has been decreasing, so that whereas at one time it was 25 years, figures as low as 20 years are now discussed. We are not aware of any precise and quantitative cost/benefit analysis of the situation, and indeed many of the factors themselves are difficult to quantify exactly. For the sake of discussion this is called the critical age.

10.6.2 The present situation in Malaysia

It is convenient to analyse the Malaysian situation, because Malaysia was the first country to have a really

large population of planted and managed palms, and any emerging problems are likely to be encountered later in other countries. The relationship of the demographics of the oil palm population, the OER problem and the apparent plateau in average yield (Tinker, 2000a) has been discussed in detail by Jalani *et al.* (2001), using the excellent statistics available from the Malaysian Palm Oil Board (MPOB). The Malaysian population of oil palms is curious in the sense that the annual increase has not been closely linked to the size of the adult population at that time, as happens in most biological populations (Table 10.18). The total area planted increased from 786,000 ha in 1975–1979 to 2,207,000 in 1990–1994, but the rate of addition of young palms (replanting plus new planting) remained fairly constant between roughly 260,000 and 280,000 ha. Only in 1995–1999 did the planting rate increase sharply. This is assuming that ‘Immature’ in Table 10.18 can be equated to newly planted palms. As immature usually means up to 3 years old, this 3-year period will overlap at the beginning and the end of the 5-year accounting periods. However any error is unlikely to be large.

With such a rapidly growing population, it is to be expected that some rather extreme percentages emerge. Percentages of replanting can therefore be misleading; the percentage replanted now must appear small, because it compares replanting of a relatively small group of palms initially planted some 25 years ago with the current large planted area. It is therefore better to consider the age profile of the palms (Jalani *et al.*, 2001; Khoo, 2001) (Table 10.18b). Jalani *et al.* (2001) pointed out that the percentages of palms in the oldest groups increased sharply over the whole recording period. This is a predictable result of the way in which the population was built up: the massive industry today has emerged relatively recently, and has not reached a steady state yet.

In the long run Malaysia will presumably have a steady-state oil palm industry. It can achieve this at once by replanting each year the same area that was planted the critical number of years ago. However, a more regular system seems desirable, in which approximately the same area is replanted each year, so that output of oil, and demand of labour and planting material is stabilised. This can be attained by replanting some areas a little later or earlier than the critical age, until a true steady state is achieved. The real matter for concern is that in 2000 7.77% of the population was over 25 years old, and over 21% was over 19 years old, so there is considerable delay in replanting on some estates. This supports the point made by Jalani

et al. (2001). However, in 2000 the total percentage between 1 and 8 years old was over 44%, which is encouraging, and it would become even more so if the palms over 25 years could be replaced rapidly.

This discussion is in terms of the whole Malaysian stock of palms. In 1999 the ratio of immature to mature palms in Peninsular Malaysia was 10.0%, in Sabah 23.0% and in Sarawak 37.6%. Hence, the replanting problem seems to lie in Peninsular Malaysia, and data on palms there over the age of 20 years need to be assessed critically.

The national stock of oil palms belongs to many organisations and individuals, and cannot be managed as a single estate. The owners respond to financial incentives, and Jalani *et al.* (2001) considered that the high oil prices in 1997/98 caused estates to delay replanting so as to maximise revenues, but that with subsequent low prices they cannot afford to replant. A short-term replanting grant was offered by the government in 2001, but it may be necessary to make this a permanent system (Jalani *et al.*, 2001). Ultimately, the industry must reach a more or less steady state, in which a constant land area is used for palms, and is replanted whenever the palms reach the critical age. However, the argument at the end of Section 10.5.2 shows that this will not cure the OER problem.

10.7 SITE POTENTIALS IN RELATION TO PLANTATION MANAGEMENT

10.7.1 Definition of yield potentials

It might be thought more appropriate to discuss site potential in Chapter 8 than in relation to maintenance and care. However, this placement in Chapter 10 is intended to stress that the site potential is also an important parameter to guide management of a plantation. Management often operates by carrying out all operations according to normally accepted standards, and simply accepts the yield that this delivers as normal for that field. Instead, one should start from the other side of the equation, by deciding upon what the field could deliver (the site potential), and then expecting the manager to deliver close to this yield, or to explain why it is not possible to do so (Tinker, 1984). The site yield potential (SYP) is the yield obtained on a specified site, with natural water supply, nutrients supplied at optimum rates, and agronomic and disease control measures implemented to a high standard.

Evans and Fischer (1999) discussed the various concepts of yield potential in detail. Their definition of

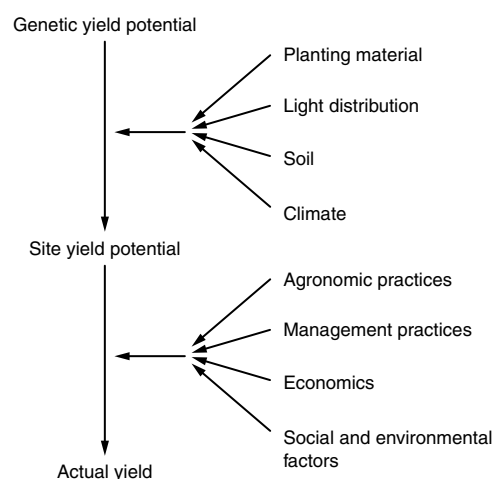


Fig. 10.11 Schematic definition of the factors affecting the site potential yield and the actual yield of a crop. (After Goh *et al.*, 1994c.)

what they called the genetic potential is ‘the yield of a cultivar when grown in environments to which it is adapted; with nutrients and water non-limiting; and with pests, diseases, weeds and other stresses effectively controlled’. This definition is weak on ‘non-limiting nutrients and water’, since both of these can be supplied to excess, or nutrients can be unbalanced. The attention in their work is focused on the properties of the plant rather than those of the site on which it is growing. The genetic yield potential is defined for present purposes (Goh *et al.*, 1994c) as the largest yield obtainable with that plant material if all the environmental conditions (site factors) and the agronomic interventions are perfect (Fig. 10.11). The distinctions between site factors and agronomic interventions are not always clear-cut; thus, the decision on planting density is an agronomic intervention before planting, but is more like a site factor afterwards, unless thinning is carried out.

The genetic potential can also be approached by physiological analysis of the processes involved in growth and yield in the palm (Corley, 1983b, 1985). There are some uncertainties in that there are many variables, and some parts of the process, such as carbon used below ground, may have to be ignored. Corley (1983b) estimated the dry matter production of the oil palm as 44 t/ha per year, including growth and leaf and inflorescence production. He estimated that this would include 17 t oil/ha plus kernels (economic product), which is well beyond any recorded yield to date.

In Corley (1985) good yields in favourable environments were stated as 5–6 t oil/ha, and the highest recorded yields as 10 t/ha. In the period since then the best recorded yields have increased to 12–13 t oil/ha. It would be helpful if a genetic yield could be estimated from physiological data, but the best available figures at present seem to be a little above the highest recorded yields, and we might assume that the present effective genetic potential is 12–14 t oil/ha. Ooi *et al.* (1990) claimed that the maximum FFB yield was around 44 t/ha in small experimental plots (FFB is fresh weight; dry weight would be about half of this). The oil yield would be around 10 t/ha, depending on the oil/bunch ratio, in agreement with the above. Yields of up to 37 t/ha have been reported in fertiliser experiments, although the use of small-plot results to predict full-field results is hazardous. However, yields of the same magnitude have also been reported in commercial fields (Goh *et al.*, 1994b, c). Very high yields have been reported since then; for example, Kee *et al.* (1998) reported peak yields in the range of 35–42 t/ha. It therefore appears likely that the site potential for modern material growing on the best sites is over 40 t FFB/ha, and presumably the genetic potential is a few tonnes higher. The oil yields will of course depend on OER.

This genetic potential is then constrained in two broad ways. Site factors are those that are only altered with difficulty: climate, soil series, etc., some of which are less than ideal, and their net effect gives the SYP. This, in turn, is constrained by agronomic factors, which are relatively readily altered by the farmer or manager. These include fertiliser treatment, pruning system and cover control. The test of the manager is whether he can manage all these factors successfully, and produce an actual yield that is close to the SYP.

10.7.2 Site yield potential

The advantages of being able to predict SYPs for all fields are obvious. Land evaluation combined with genetic potential leads on logically to SYP for oil palms (see Section 8.1.5). This concept is now used widely in Malaysia, and it forms a logical way to approach the question of the value of a specific site for a crop (Tinker, 1984; Goh *et al.*, 1994c; Kee *et al.*, 1998), and how the yield obtained by a manager should be assessed. The invariant site factors for palm growth and yield include soil texture, slope and climate, which cannot in practice be changed. If there is a disease with no known treatment, and the site is liable to suffer from this, then this will also be an invariant site factor, so there is some flexibility in the definition of site factors. The management factors are all the

treatments and inputs that can be applied that may affect the yield. If desired, these can be divided first into semi-variant factors, such as palm spacing and plantation layout, which can rarely be altered after the development of the plantation. Secondly, there are the fully variant factors that can be decided each year or even more frequently, such as fertilising, spraying, harvesting system and all other agronomic inputs. The site potential sets a limit to the plantation output, but a particular manager may fail to reach this level because of lack of care, shortage of labour, the high cost of inputs or disease (Table 8.4) (Kee *et al.*, 1998).

10.7.3 Principles and calculation of site yield potential

Yield curves for high-yielding palms (Fig. 10.12) indicate a fairly consistent pattern of yield with age. From these data it seems that the age-linked declines in yield occur at roughly the same age of 20 years. It is not clear whether this is a wholly physiological decline or due to difficulties in harvesting, or a mixture of these. However, this is not so true if the high yield sites are grouped according to whether the local climate includes a dry season or not, as in the proposed age–yield profiles for different grouped agroecological zones (Fig. 8.2). Zone A, with no dry season, includes Sabah estates; the yield peak is largest, but the age-linked decline sets in from about 15 years. The estates with a marked dry season (C) had a low peak, but maintained their yield until 22 years. However, this group included some slow-growing palms that could easily be harvested at this age, so the results may partly depend on harvesting problems. More research on change with age is needed.

The full data show that all soil series, except for the Malacca series with plinthite, gave some yields at over 30 t/ha (Table 10.19) (Goh *et al.*, 1994c). This survey covers thousands of hectares and over 200 fields and the attainment of over 30 t on almost all of them is encouraging. Tinker (1984) studied UK survey data on wheat (Fig. 10.13a). He concluded that very high yields (of over 10 t/ha) could be obtained on the great majority of soils with excellent agronomy and high inputs, but that the high frequency and reliability of the best yields marked out the good sites. Goh K.J. (pers. comm.) found that plotting FFB yields of oil palm blocks in a similar way also produced Gaussian distributions, with no cut-off in yield at the highest values (Fig. 10.13b). As shown in Table 8.5, the variability of annual FFB yields also differed between soil series for oil palms. The correlation between the yield at 4 years and the probability of attaining over 30 t/ha

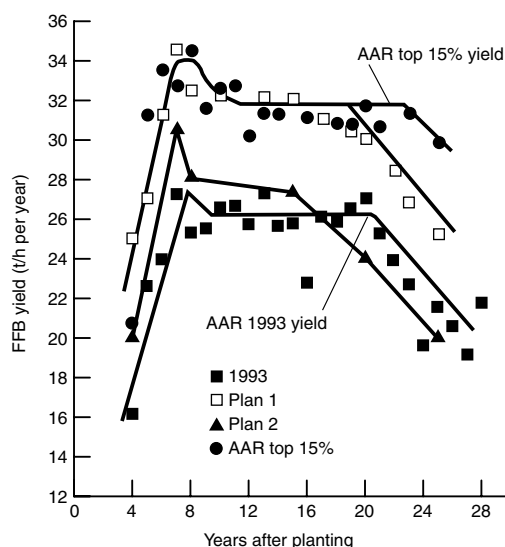


Fig. 10.12 Distribution of yields with age, for yields in 1993 on all AAR-advised estates, for fields with yields in the top 15% of the AAR estates, and for the yields obtained by Ng and Thong (1985) using two maximum exploitation of genetic yield potential plans. (After Goh *et al.*, 1994c.)

later was very high, and Goh *et al.* (1994c) ascribed the correlated poor yields in this case to the presence of a dry season, shallow soils or 'agromanagement errors'.

This suggests that Gaussian curves for different soil series, drawn from data for individual field yields,

would have different spans and shapes. The latter might be used in SYP assessments for soil series.

This approach has been developed into a full yield-prediction system (ASYP, the AAR site yield potential model) (Kee *et al.*, 1998). This basically works by combining a series of site yield factors in a multiplicative equation:

$$\text{SYP} = f(F1 \times F2 \times F3 \times \dots) \times \text{Genetic potential} \quad (10.1)$$

The main factors were (Kee *et al.*, 1998):

- type of planting material (the genetic potential)
- light interception, determined by planting pattern and crown density
- soil factors affecting rooting, e.g. soil depth, structure, depth
- climate: mainly the magnitude and duration of the annual soil moisture deficit
- palm age. (Figs 10.1 and 8.2.)

The full details of the system have not yet been published.

For young palms in one experiment, ASYP 2.6 (the then current version) predicted the increasing yield pattern over the early period. The outcome for the experiment is shown in Table 10.20. Overall, the difference between predictions on the ASYP model and the outcome was <8%. Unexpected pest attack or abnormal weather cannot be predicted, and could prevent good agreement.

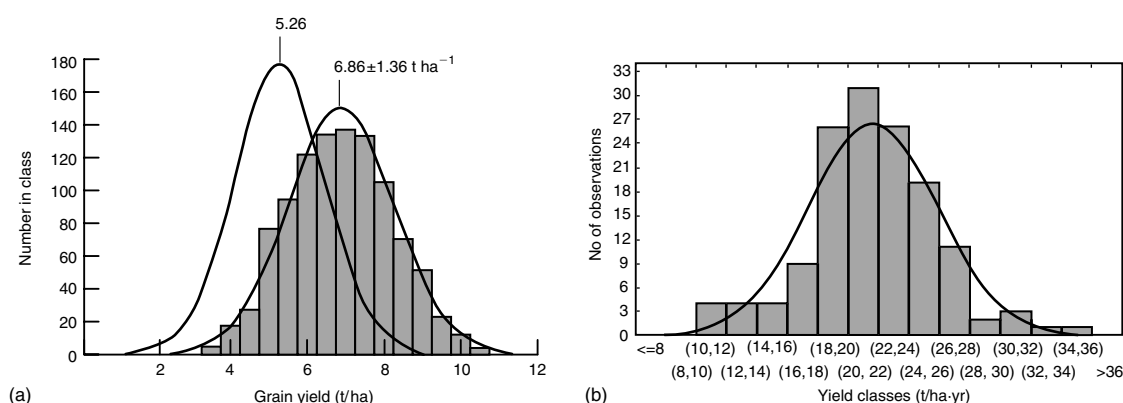


Fig. 10.13 (a) Frequency distribution of wheat yields in England in 1979. Histogram of yields from farmers fields given the best possible treatment for that field. The full curves are the expected distribution for the national crop (after Tinker 1984) (b) Frequency distribution of yields in blocks of palms in Peninsular Malaysia, of age 16–20 years old. Smooth curve is a Gaussian distribution (from Goh K.J., private communication).

Table 10.19 Mean yields, range of yields and percentage response to fertilisers on experimental plots or commercial blocks of palms, on a number of different soil types on Peninsular Malaysia and Sabah

Soil region	Soil series	No. of fields	Area (ha)	Weighted FFB (t/ha per year)		% Response ^a	Site use
				Mean	Range		
Peninsular Malaysia							
Coastal	Selangor	2	Plot	35.6	35.1–36.1	3–20	Experiment
	Briah	6	Plot	28	26.4–31.1	10–44	Experiment
	Carey	2	Plot	29.9	27.8–31.9	24–50	Experiment
	Sedu	1	Plot	31.2	–	3–7	Experiment
Riverine	Sogomana	9	511	32.8	29.9–36.3	–	Commercial
	Sitiawan	7	263	30.4	29.7–38.5	–	Commercial
	Rasau	6	213	33.8	29.6–34.5	–	Commercial
	Holyrood	10	849	32.5	29.9–37.7	–	Commercial
	Lunas	1	30	32.3	–	–	Commercial
	Harimau	1	26	38.0	–	–	Commercial
	Inland	Munchong	13	598	32.1	29.8–35.9	–
Munchong		3	Plot	31.7	29.9–34.6	23–198	Experiment
Prang		3	118	34.1	30.8–35.3	–	Commercial
Serdang		2	77	32.1	31.3–33.2	–	Commercial
Serdang		1	Plot	32.3	–	169	Experiment
Bungor		1	Plot	31.8	–	270	Experiment
Jerangau		5	309	30.6	29.7–32.0	–	Commercial
Lanchang/ Jerangau		129	1,997	30.7	29.5–35.5	–	Commercial
Rengam		26	1,327	31.3	29.5–34.6	–	Commercial
Rengam		1	Plot	27.7	–	52	Experiment
Lambak		1	24	32.5	–	–	Commercial
Baserah		1	68	30.1	–	–	Commercial
Durian		1	80	29.7	–	–	Commercial
Durian		3	Plot	31.2	25.6–36.8	35–183	Experiment
Tavy		3	127	31.7	29.8–34.6	–	Commercial
Tandak		1	13	30.9	–	–	Commercial
Malacca		5	116	23.4	20.2–27.9	–	Commercial
Malacca		2	Plot	28.6	27.9–29.3	8–28	Experiment
Batu Anam		3	Plot	29.1	25.5–33.0	17–47	Experiment
Sabah							
Riverine	Koyah	7	291	37.5	35.3–39.4	–	Commercial
	Paliu	7	727	31.5	29.6–37.1	–	Commercial
	Inanam	1	106	30.8	–	–	Commercial
Inland	Kumansi	33	2,229	32.1	29.9–36.8	–	Commercial
	Batang	2	154	32.5	31.2–33.6	–	Commercial
	Sipit	4	257	31.9	31.0–37.8	–	Commercial
	Tg. Lipat	8	493	35.8	30.0–36.0	–	Commercial
	Apas	3	319	35.4	31.8–39.8	–	Commercial
	Baiayo	3	112	26.1	22.3–28.7	–	Commercial

^a % response over the control plot without manuring.

After Goh et al. (1994c).

Table 10.20 Calculated prediction with ASYP 2.6 of site yield potential, and comparison with best and mean treatments in fertiliser experiments established to test this method (t FFB/ha)

	Year					Total ^b
	1993	1994	1995	1996	1997 ^a	
Age (years)	3	4	5	6	7	–
ASYP 2.6	19.4	26.1	31.6	36.0	19.6	113.3
Trial mean	10.9	23.5	30.8	32.8	17.9	105.0
Best trt ^c	11.5	24.9	33.3	34.3	20.1	112.6
% ASYP2.6	59.2	95.4	105.3	95.2	102.5	99.3
Next best ^d	11.4	25.8	32.0	35.6	18.7	112.1
% ASYP2.6	58.7	98.8	101.2	98.8	95.4	98.9
Control	9.5	23.0	29.8	28.6	17.1	98.5
% ASYP2.6	48.9	88.1	94.3	79.4	87.2	86.9

^aJanuary to June 1997 (6 months only).

^bCumulative yield from 1994 to Jun. 1997.

^cBest treatment based on cumulative yield.

^dNext best treatment based on cumulative yield.

After Kee *et al.* (1998).

10.7.4 Action with fields producing less than the site yield potential

Correction of the state of a field with yield well below its SYP is not an automatic procedure, and agronomic skill and experience will always be necessary. The SYP calculation is to be seen as a warning, and blame should not necessarily be aimed at managers when it is found that the actual yield is well below the SYP. Agronomists and managers, working together and using the ASYP estimate as a target, must examine the estate very carefully for the reasons for underperformance, or the use of methods that are inadvisable. Some site factors can be corrected, although at considerable cost. Some soil conservation measures can be put in place in a bearing field, mulching with EFB can reduce a soil moisture deficit, and so on. The first step is to determine the best (see Chapter 11) input of fertilisers. The INFERS system (Section 11.6.2) is designed to operate with ASYP. Advice on leaf pruning and cover treatment can be adjusted to take account of negative factors. Kok *et al.* (2000) discussed a series of site-specific agronomic recommendations which, implemented together, should produce near to the SYP under most conditions. They gave a table showing how the actual yield in 10 fields, some having lateritic soils, approached the estimated yield potential over the period 1984 to 1992, in 3-year periods. In the final period the potential and actual yield were within 2 t/ha of each other in all except one field. Improved expert systems are projected for the future.

A simpler approach to what is essentially the same question of potential and actual yields has been presented by Griffiths *et al.* (2002). This names Best Management Practice as the procedure for eliminating yield gaps, that are identified by determining the potential yield. The estimation of potential yields in specific land classes and climates is done by planting test blocks with, as far as possible, ideal treatment. This demands fertiliser experiments on each land class, and carefully supervised harvesting to eliminate losses. Pests, diseases, weeds and covers must be controlled 'according to estate standards'. This is not wholly clear, because estate standards may intentionally aim for maximum profit rather than maximum yields (though the two yield levels are usually close). The essence of the system is thus to grow blocks with best treatment, and take this as the potential yield. A computerised database and a GIS system are used to manage the mass of data produced by the system. Potential yields are not corrected for differences in rainfall. There appears to be no systematic method of combining and extrapolating data for intermediate land classes, so a test block and factorial fertiliser experiment on each land class could become expensive.

10.7.5 Remote sensing of palm conditions

Remote sensing methods have been discussed for a long time in oil palm research groups, but little application

has yet occurred. The first possibility is to use them in developing a plantation (Section 8.1.3.2). Further, with the yield potential methods discussed above, there is a need to provide spatially detailed information both to indicate differences in the palm conditions in different areas, and to suggest causes of underperformance (Lukman Fadli and Poeloengan, 1996). Remote sensing is therefore discussed briefly here.

Several groups have used multispectral SPOT (Satellite pour l'observation de la Terre) imagery to identify oil palm field properties. Despite its high resolution, Naert *et al.* (1990) found some difficulty in obtaining reliable images, owing to cloud cover, disease appearance, or varying environmental factors such as water and plantation age or seasonal condition. However, links were found between near infrared reflectance and the leaf nutrient contents of nitrogen, phosphorus, magnesium and sulfur. It is surprising that potassium is not part of this list, which otherwise appears to contain the elements whose deficiency is most likely to cause leaf chlorosis. Nguyen *et al.* (1995) also used SPOT imagery, and obtained a variety of interesting correlations, but it seems uncertain how dependable they would be. McMorro and Tey (2000) and McMorro (2001) discussed the possible value of Landsat imagery. This has lower resolution than SPOT, but there is much more data available, and the system is well established. It is likely that age of palms and the *L* could be determined from Landsat material. A plantation manager is supposed to know the age of his fields, so this does not seem an important breakthrough, but the ability to detect and measure canopy density could be useful. Rosenquist (1996) tested the use of backscattered radar signals from the satellites JERS-1, ERS-1 and ALMAZ. The last was of little value, but the signals from the others could estimate the *L* of oil palms successfully. Fairhurst *et al.* (2000) focused on the GIS that are now readily available. These will handle digitised maps of agronomic soil and plant data, and derived data from these, such as a soil carbon/nitrogen ratio. Chew and Abdul Rahim (2000) found that it was technically possible to construct yield maps with GPS/GIS techniques, and thereby approach the possibility of precision agriculture (Chew, 1998).

Remotely sensed images may well be of use in managing a plantation, but it would be surprising if an alert manager were not already aware of most faults. They may be more useful to higher management. As a rapid oversight, remote sensing is valuable, but it is unlikely to contribute to the detailed correction of faults and deficiencies that are the essence of the process of moving close to the SYP.

10.8 SMALLHOLDER PLANTATIONS

10.8.1 General

The oil palm is unusual for a tropical crop in that a large and expensive mill is needed to deal with the bunches immediately after they have been harvested. This makes it difficult for independent smallholders to grow oil palms, unless there is an oil palm mill available nearby. Therefore, there are considerable economic and social advantages in grouping smallholders around a 'nucleus' estate, to supply some of the fruit that it needs to mill. The mill can therefore be more fully utilised with a larger throughput, and this system has been widely used. The technical problems centre on encouraging the smallholders to maintain palms well and harvest them regularly. Their harvesting has to be integrated with transport to the mill, often provided by the mill or nucleus estate. A smallholder group is therefore seldom as efficient as a good estate, and the system has not yet been studied during a period with very low prices. In Malaysia the competition with alternative jobs is felt very strongly. The production structure of the Malaysian smallholder industry has been discussed by Malek and Barlow (1988).

10.8.1.1 Malaysia: FELDA

The largest smallholder development organisation is the Federal Land Development Authority (FELDA) in Malaysia, which was set up in 1956 to encourage smallholder developments (see Chapter 1) (Shamsul Bahrin and Lee, 1988). FELDA has been unusual in not using the system of a nucleus estate that is permanently run by the developer, because it wished to have as many settlers as possible. These smallholder developments were not the only ones in Malaysia, but they were by far the largest, and they were originally targeted at growing food crops, rubber and oil palms. Subsistence farming was not the objective, and cultivation of food crops diminished. Rubber was then by far the largest Malaysian crop, but FELDA encouraged a movement into oil palms. The steady growth in the expectations of the settlers with rising national prosperity, and the decrease in the real prices of commodity products, meant that the initial size of the land allocation had to be increased. In oil palm schemes the land for palms allocated to each farmer was 3.2 ha. Settlements of 400–600 families were set up, within schemes that might be up to 8000 ha. The choice of land was governed by social factors and topography. The upper limit on slope was 20%, which is rather steep.

Accessible areas with good soil, as defined by the Agriculture Department, were selected.

FELDA oil palm schemes therefore had an estate-based pattern of work but with a co-operative land holding system. Settlers were carefully trained in cultivating oil palms over a period. This produced trained harvesters and regular harvesting, and hence high quality oil and good yields. Gradually, FELDA set up seed production facilities and a fertiliser research programme. At one time FELDA applied much fertiliser by air over large areas of plantation, but by 1979 this had ceased; it was too expensive and more convenient methods were available. Nearly all of FELDA's schemes were on logged-over forest. There was consequently an elephant problem, and large numbers of oil palms were destroyed by the animals. This was eventually stopped by capturing and relocating the elephants further into the forest. On average, FELDA has produced 23 t/ha in the seventh year of planting, which is respectable. The crop is now FELDA's mainstay, with over 500,000 ha producing 24% of national production and 14% of world production in 1985.

10.8.1.2 Indonesia

Smallholder schemes have also been established in Indonesia in the Nucleus Estate Smallholder (NES) scheme (Lubis *et al.*, 1993). By 1989 this had 177,831 ha and involved nearly 89,000 families. These smallholdings are grouped around a larger nucleus estate, which is basically a normal oil palm estate of moderate size. It has a mill and buys the smallholders' fruit, and provides other services such as advice, sales of fertiliser and possibly lorry transport for FFB. After a conversion period the farmers will be fully responsible for managing the farms and selling their produce. The aim has been that

a farmer should earn about US\$1500/year, but many earn less than this.

10.8.1.3 Papua New Guinea

The first smallholder scheme was set up in 1968 as the Hoskins Oil Palm Scheme. (King *et al.*, 1998). A nucleus estate had been set up earlier, with 500 smallholder blocks planned. Later, the scheme was extended to 4000 ha of estate and 6000 ha of smallholdings. Each settler received 6 ha of land, and undertook to plant 4 ha with palms within 2 years of taking over the block and to remain there for 7 years. The farmers were responsible for all planting and normal upkeep and maintenance. Harvested fruit was picked up by estate lorry for transport to the mill. The average income per farmer was about US \$2400, with acceptable yields (Table 10.21), although these yields were much lower than those of 25 t/ha obtained by the estate. New Britain Palm Oil Ltd is the management company, which produces seedlings, sets up experiments, runs the estate and advises the farmers. The farmers participate in experiments, and as a result of these they have been advised to apply fertilisers, with excellent results.

Table 10.21 Production statistics for a smallholder development in Papua New Guinea

Year	Mature area (ha)	Production (t FFB)	Yield (t/ha)
1993	10,600	123,008	11.6
1994	10,900	119,897	11.0
1995	10,600	127,437	12.4
1996	9,950	147,175	14.8
1997	9,270	152,500	16.5

After King *et al.* (1998).

Chapter 11

Mineral Nutrition of Oil Palms

11.1 GENERAL PRINCIPLES OF PLANT NUTRITION

11.1.1 Introduction

The general principles governing the mineral nutrition of plants in soil are by now fairly well established (Nye and Tinker, 1977; Barber, 1995; Marschner, 1995; Tinker and Nye, 2000). However, the quantitative prediction and control of nutrition in the field, and the detailed physiology of the whole-plant system still contain many unsolved problems. The nutritional physiology and biochemistry of the plant (Marschner, 1995; Mengel and Kirkby, 1996) will not be dealt with in detail here, as it is very complex and at present has rather little direct relevance to the management of oil palms in the field. The focus here will be on how to determine and apply the optimum amounts of the various nutrients for maximum profit over the plants' life, and for the least possible impact on the environment, but some of the scientific background will be dealt with if it clarifies the field problems.

11.1.2 Essential elements

The plant is mainly composed of carbon, hydrogen and oxygen (see Section 4.1.1). This is particularly relevant for the oil palm, because the palm oil used in commerce also contains almost entirely carbon, hydrogen and oxygen. However, the plant also contains a huge range of more specialised compounds, which may fulfil essential functions or be more like waste products, and which may contain various elements.

An essential element is defined as one without which the plant is unable to complete its life cycle (Corley, 1976; Marschner, 1995). Essential nutrients fulfil many functions in the plant. Some, particularly trace elements, are components of enzymes that control essential reactions. Others are part of large classes of compounds, such as nitrogen (N) and sulfur (S) in proteins or N and phosphorus (P) in nucleic acids, or have general

functions, such as potassium (K), which affects many solution equilibria throughout the plant, including pH and acid–base balance. In all, 13 elements are considered to be essential for the great majority of plants. Of these, N, P, K, magnesium (Mg), calcium (Ca) and S are major elements that plants contain in some quantity. Zinc, copper, iron, boron, molybdenum, nickel and chlorine (Zn, Cu, Fe, B, Mo, Ni and Cl) are trace elements that are present in low concentrations and found to cause deficiencies in the field much less frequently, although they are mostly just as essential as the major elements. A few other elements are beneficial in some species, but not essential; these include sodium, silicon, selenium, cobalt and aluminium (Na, Si, Se, Co and Al) (Marschner, 1995). Certain additional elements are needed by lower plants.

Oil palms are fairly normal in their composition, with the exception that chlorine is beneficial in some circumstances, owing to processes that are still not understood (Section 11.4.5). The majority of elements (N, P, K, Mg) can be recirculated in the plant, via the xylem for upward mobility and the phloem for general mobility (Marschner *et al.*, 1997). When one of these elements becomes deficient, it is expressed in visible symptoms or low tissue concentration, both mainly in the older leaves because of internal retranslocation. The less mobile elements (Ca, Fe) are not phloem mobile, and their deficiencies are therefore observed in the growth points.

An example of the concentrations of the various elements in a non-deficient mature oil palm is shown in Table 11.1 (Ng *et al.*, 1968). A fully fertilised palm under present conditions would probably have some higher concentrations.

11.1.3 Plant demand

The requirement for essential elements by a growing plant is called plant demand. It is logical to consider the total demand of a plant as composed of two separate processes: growth demand and deficiency demand (Tinker and Nye, 2000). The underlying theory of these

Table 11.1 Mean nutrient concentration in the tissues of 8–15-year-old palms grown in Malaysia

Component	N	K	P	Mg	Ca	S
Pinnae	2.05	0.88	0.128	0.233	0.356	0.174
Rachis	0.37	1.49	0.074	0.193	0.213	0.182
Spear	1.33	1.70	0.140	0.198	0.187	0.157
Cabbage	2.86	4.06	0.550	0.920	0.422	0.409
Trunk	0.54	1.54	0.070	0.168	0.179	0.311
Roots	0.32	0.80	0.027	0.083	0.048	0.308
Whole palm	0.54	1.60	0.078	0.160	0.180	0.296

Ng *et al.* (1968, p. 388).

two 'demands' is as follows, based on the equation of Tinker and Nye (2000):

$$\text{Nutrient amount in palm } N = XW$$

$$\text{Uptake rate} = d(N)/dt = X dW/dt + W dX/dt \quad (11.1)$$

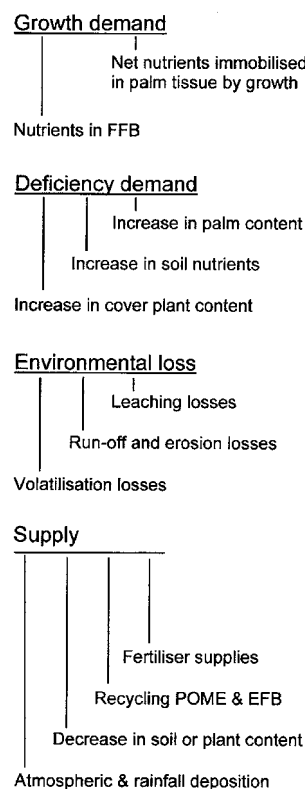
where N is the total nutrient in the palm, W is the mass and X is the fractional content of the nutrient. The first term represent the growth demand, because the nutrient percentage remains constant as the plant grows at a rate dW/dt . However, during the correction of a nutrient deficiency, the second term applies, as the weight is constant but with a varying nutrient concentration. In fact, both processes occur at once. Without the differentials and ignoring change in structure of plant material, a simple approximation for the uptake is:

$$X_2(W_2 - W_1) + W_1(X_2 - X_1) = X_2W_2 - X_1W_1 \quad (11.2)$$

for times t_1 and t_2 , where the meaning of the terms remains the same.

11.1.3.1 Growth demand

This arises from the enlargement of the plant organs and the production of any plant parts that are removed, such as fruit bunches. In the oil palm, the continued growth of the trunk throughout the palm's life, and the continued production and removal of fresh fruit bunches (FFB) means that all nutrients contained in these new parts are additions, and hence part of the plant growth demand. The position of the leaves and the male inflorescence is more complex. Nutrients for the leaves and roots are certainly vital, and part of their uptake is growth demand during the stage of increasing size of the crown and root system. However, a net uptake of these amounts may not be needed in a mature palm, because as older leaves senesce, their contained nutrient may be

**Fig. 11.1** Nutrient cycles for potassium in oil palm plantations.

recirculated quite rapidly (Kee and Chew, 1997) back within the palm. Further, nutrients in the dying leaves may be washed out by rainwater or, failing that, will finally enter the soil as the dead leaves and inflorescences decay, and will be available for uptake again (the inner cycle) (Fig. 11.16) (Section 11.7.5). In consequence, the nutrient in the crown and inflorescences, and probably the roots, of a mature palm is an almost constant quantity, although it is being cycled all the time. It therefore only contributes to the net growth demand when the size of the canopy is changing, which is rapidly up to 3 years, and then more slowly up to 8–10 years.

It is now normal for empty fruit bunches (EFB) and palm oil mill effluent (POME) to be returned to the palm field from which the FFB originally came (the outer cycle) (Fig. 11.16) (Section 11.7.2) (Hornus and Nguimjeu, 1992). If all these nutrients could be returned, then the FFB yield would not contribute to the growth demand either. In practice, 100% recycling is never attained, because the kernels contain nutrients, and because some part of the FFB nutrient content is always lost in the mill operations. The amount recycled

in these two cycles will vary widely with the nutrient in question and the management of the plantation, but the total amount in leaves and inflorescences will usually be fully recycled. The growth demand can therefore be calculated from the increasing dimensions of the palm trunk, the nutrient concentration of the plant parts, and the FFB demand less any returned nutrient. Ideally, the system as a whole is in a steady state. This is the underlying theory of the nutrient balance approach to fertilisation (Section 11.5.1). Ng (1976) was the first to emphasise the value of this method for oil palms.

11.1.3.2 Deficiency demand

The outline in Section 11.1.2 assumes implicitly that the palm is in a satisfactory nutritional state, but this is often not correct. If it is deficient, then it requires an extra supply of nutrients to raise the concentration throughout the palm to that which is essential for the maximum growth rate and rate of production of FFB at its site yield potential (SYP) (Sections 10.7.2, 11.4.2). This can be computed if the necessary concentrations in the various organs are known. In practice, this can be predicted from the usual leaf analysis data, as there is a reasonably dependable relationship between the amounts of nutrients in the leaflets and in all the other plant organs (Goh, K.J. pers. comm.) (Section 11.4.2). If the deficiency demand is met it implies that as the deficiency is corrected, the palm canopy and the number of inflorescences and the FFB are likely to become larger and heavier, so that the growth demand will also increase. This must be taken into account in the growth demand calculation. The soil composition also has to be increased to ensure that the new and higher inflow rate to the roots (Section 11.2.3) can be met, so that the improved concentration within the plant becomes permanent. This may well be the largest component of the deficiency demand. There is no specified period over which the deficiency demand must be met, but if the required amount of nutrient is of moderate size, it should happen within 1 year.

This concept can be understood better by considering the work of Warriar and Piggott (1973). In a long-term fertiliser experiment the palms on different plots ranged from being well supplied with nutrients to seriously deficient. The plots were then given new fertiliser dressings based on their leaf composition data. After 2 years of corrective manuring, with a total of four fertiliser applications, the mean yields on the original control plots had increased from 71 to 92% of the experiment mean for increased N, 90 to 93 for P and 81 to 92 for K. Maximum mean yields over 3 years for palms that had been well fertilised in the original experiment were 115 for N2

Table 11.2 Mean nutrient concentration (% of dry matter) in the tissues of 7-, 14- and 20-year-old palms near Benin City in Nigeria, which received no fertiliser; some data are for palms extremely deficient in potassium and magnesium

Age (years)	Part	N	P	K	Mg	Ca
7	Leaflets	1.64	0.12	0.95	0.27	0.55
	Rachis	0.41	0.07	0.84	0.16	0.25
	Apical tissue	2.20	0.38	3.30	0.80	0.82
	Trunk	0.52	0.07	0.47	0.21	0.22
14	Leaflets	1.90	0.13	0.70	0.36	0.68
	Rachis	0.37	0.06	0.43	0.14	0.28
	Apical tissue	2.18	0.36	2.55	0.91	0.73
	Trunk	0.55	0.07	0.36	0.17	0.15
20	Leaflets	1.94	0.14	0.77	0.38	0.78
	Rachis	0.33	0.08	0.26	0.28	0.47
	Apical tissue	2.00	0.40	1.75	1.00	1.00
	Trunk	0.44	0.07	0.19	0.34	0.26
22 K-deficient	Leaflets	1.82	0.15	0.48	0.46	0.92
	Rachis	0.38	0.08	0.20	0.43	0.64
	Apical tissue	2.00	0.48	1.61	0.99	0.87
	Trunk	0.40	0.08	0.16	0.30	0.19
21 Mg-deficient	Leaflets	1.63	0.12	0.99	0.07	0.20
	Rachis	0.45	0.10	0.60	0.05	0.12
	Apical tissue	3.00	0.47	3.33	0.53	0.53
	Trunk	0.64	0.08	0.50	0.03	0.17

After Tinker and Smilde (1963b).

level, 108 for P2 and 111 for K2. A large but still incomplete recovery had occurred, and the authors concluded that the deficiency demand had been met in 2 years. However, the plots that originally had zero applications of any one nutrient still lagged well behind. It is not possible to conclude from the experiment whether the long-established deficiency demand could have been met more rapidly with heavier corrective dressings, or whether a delayed recovery of this type is physiologically controlled.

11.1.4 Nutrient content of oil palms, nutrient budgets and nutrient balance

The measurement of the uptake and allocation of all nutrients used by oil palms is a major task. The nutrient concentrations of the various palm parts was measured, including the trunk, for groups of palms of increasing ages in Nigeria, without fertiliser (Table 11.2) (Hartley, 1988). When the contents were plotted against time

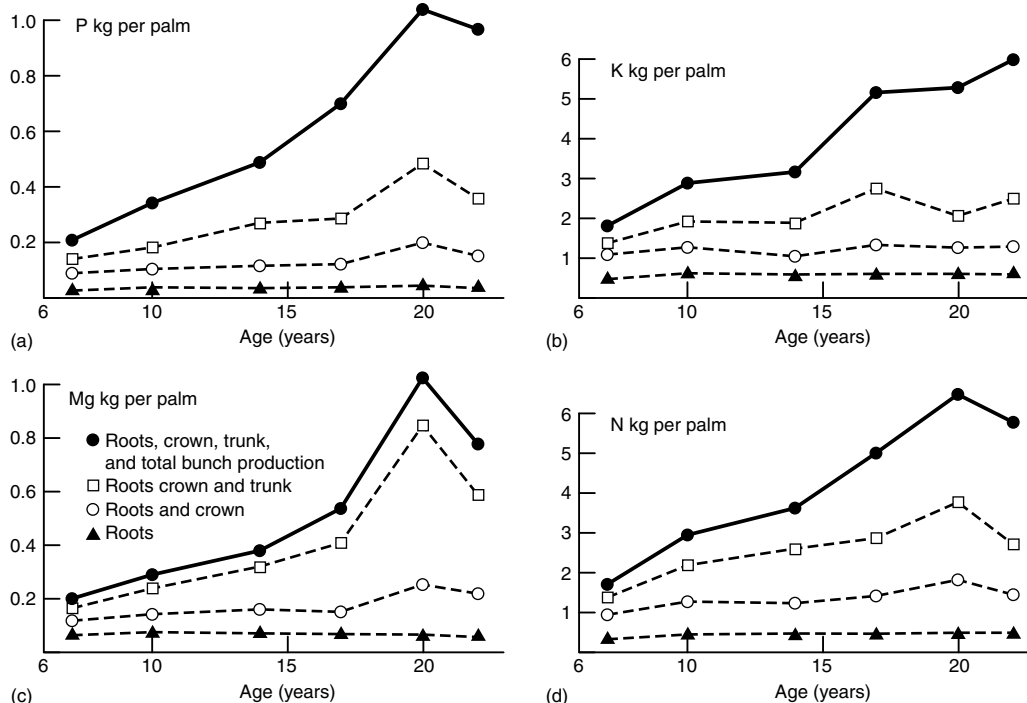


Fig. 11.2 Cumulative uptake of phosphorus, potassium and magnesium in unfertilised palms in Nigeria. (After Hartley, 1988.)

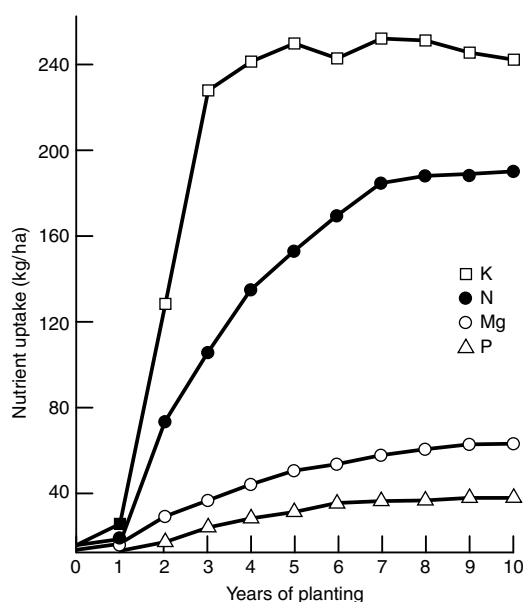


Fig. 11.3 Nutrient uptake rate of nitrogen, phosphorus, potassium and magnesium by oil palms in Malaysia up to 10 years after planting. (After Ng, 1977.)

(Fig. 11.2) (Hartley, 1988), the slope gave the mean net annual change in the total contained nutrient for any specific age. This, together with that contained in the FFB yield, gives the basic annual growth demand.

Measurements of palm composition have been made in Nigeria, Congo and Malaysia (Hartley, 1988). There is a strong suspicion that the older African palms were nutrient deficient, most probably in potassium. The nutrient need is much greater in the fertilised Asian palms, owing to more rapid growth and in particular to greater FFB output, but the relationships are in principle the same (Fig. 11.3). The most notable result for almost all data of this type is the high nutrient content, especially potassium and sulfur, in the palm trunk (Fig. 11.4) (Ng *et al.*, 1968). The large amount and the variability of nutrients with position on the trunk are almost certainly consequences of the fact that all parts of the trunk of the palm remain alive. In contrast, the trunks of most trees consist of large amounts of functionally dead lignified xylem, with a thin layer of living cambium on the surface.

Taking the point of maximum mean slope from Fig. 11.2 (Tinker and Smilde, 1963b) and converting to a per hectare basis assuming 143 palms/ha, the values of net nutrient uptake for the Nigerian palms are approximately

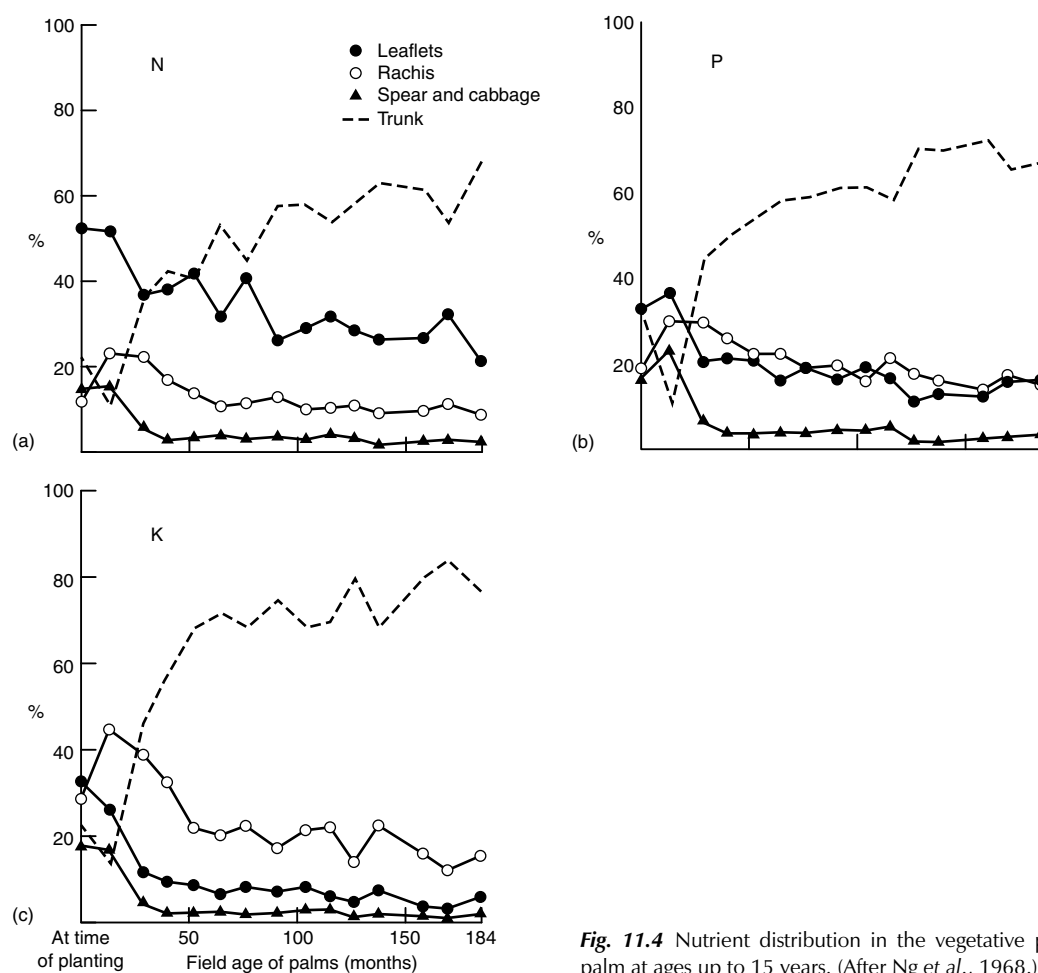


Fig. 11.4 Nutrient distribution in the vegetative parts of a palm at ages up to 15 years. (After Ng *et al.*, 1968.)

Table 11.3 Nutrient uptake and loss in bunches for oil palms in Malaysia

	Uptake (kg/ha per year)				
	N	P	K	Mg	Ca
1. Gross nutrient uptake (G)	193	26	251	61	89
2. G, less leaves and male inflor.	144	15	149	32	23
3. Bunches 25 t/ha·yr	73	12	93	21	20
Net total (2 + 3)	217	27	242	53	43

	Nutrients (per tonne of bunches)										
	N	P	K	Mg	Ca	Mn	Fe	B	Cu	Zn	Mo
kg	2.89	0.43	3.65	0.76	0.80						
g						1.49	2.43	2.12	4.69	4.85	0.0083

After Ng *et al.* (1968) and Hartley (1988, p. 483).

Table 11.4 Net nutrient demand for oil palms measured by various authors

Nutrient demand (kg/ha per year)						
Age (years)	N	P	K	Ca	Mg	Ref.
10	114	14	149	33	32	1
15			290			
15	162	21	279	nd	49	2
	192	26	251	89	61	3
	192	26	251	nd	61	4

After Xavier (2000).

nd: not determined

References: 1: Henson (1999c); 2: Ng *et al.* (1999);

3: Pushparajah and Chew (1998); 4: Ng (1976).

66 N, 14 P, 95 K and 57 Mg, all in kg/ha per year. The corresponding figures for the Malaysian palms from Table 11.3 (Ng *et al.*, 1968; Hartley, 1988, p. 483) are generally much larger, especially for potassium: 217 N, 27 P, 242 K, 53 Mg and 43 Ca, all in kg/ha per year. Since these measurements were made over long periods, it can be assumed that the palms are in a near-steady state, and that the values are the growth demand of these adult palms. However, the Nigerian palms on Acid Sands soils were receiving no regular fertiliser dressings, so the potassium deficiency must have been increasing over a number of years. The growth demand was thus met in part by increasing the potassium deficiency.

Recent work on the net nutrient demand by palms in Malaysia has been discussed by Xavier (2000), with a summary of data (Table 11.4). Omitting one set of very low values for young palms, the annual uptakes are about 190 N, 25 P, 270 K, 90 Ca and 60 Mg, all in kg/ha per year. More detailed data are presented in Teoh and Chew (1988b) for potassium. From Table 11.5 (Teoh and Chew, 1988b) it seems that on average, assuming that near to full size crown was attained at the age of 5 years, the total content (not the total uptake) increased by approximately 1 kg K/palm per year. The content in the fruit bunches ranged from about 4 to 5 g K/kg fresh bunch, or up to 1.12 kg K/palm per year, with a mean annual FFB yield of 150 kg/palm, giving a total uptake of around 2.12 kg K/palm per year, which is rather larger than the other figures given above, at 300 kg K/ha per year with 143 palms/ha. This is assumed to be the growth demand. However, the net uptake per year varies widely between different fields and measurements (Table 11.5), and any average value must be very rough. Potassium may vary more widely in concentration in palm tissues and in FFB than most other elements.

The discussion above might suggest that the palm field must be in a steady-state condition, if the measured

losses from the external nutrient cycles (Fig. 11.1) are exactly supplied by fertiliser. However, there are other very significant losses in soil leaching, erosion and runoff and in atmospheric losses for nitrogen (as ammonia and nitrous oxide), as well as nitrogen gains in leguminous cover plants (Section 11.7.4). Here, this is called the environmental demand (Fig. 11.1), and these losses need to be replaced. Short-term measurements tell us little about whether the field is in a long-term steady state and, if so, whether this steady state is the most efficient one possible with the lowest nutrient content and circulation to give maximum FFB yield. Such measurements therefore cannot be relied upon to maximise profit, which requires a much more detailed approach (Section 11.6).

11.2 PALM UPTAKE SYSTEMS

11.2.1 Root system of the oil palm

11.2.1.1 Root properties and nutrient uptake

Plants can certainly absorb nutrient via their leaves, as is shown by foliar application in leaf symptom investigations. Where the mass of the nutrient is small, it may be commercially viable to apply it via a spray to the shoot of the plant, as with copper nutrition. However, by far the greater part of nutrients enters via the root. It is generally accepted that all nutrients are absorbed from the liquid phase, even when this is only a very thin layer on the outside of the root and in soil pores. Previous ideas of 'contact exchange' or 'interception' of nutrient have been abandoned, and it is accepted that nutrients move through the soil by mass flow or diffusion prior to uptake (Barber, 1995). The uptake step into the root is complicated for most essential nutrients, and the absorbing power of the root is adjusted in accordance with the plant's nutrient demand (Tinker and Nye, 2000). There is no certainty about the fraction of the root system that can absorb ions, but it is known that this fraction is different for different nutrients, and larger for nitrogen, phosphorus and potassium than for magnesium and calcium. Little or no such physiological work has been done on the oil palm.

The important issue regarding root systems is whether they can absorb nutrients and water at the necessary rate to sustain the growth rate and the transpiration rate of the plant. The length and distribution of the functional root system are therefore very important. Diffusion theory has shown that root length is more important than either root mass or volume for the uptake process of most ions and water, because of the restriction imposed by the soil on ion diffusion and water capillary movement. This is the reason for expressing the nutrient uptake rate as 'inflow', or uptake per unit time

Table 11.5 (a) Distribution of total potassium in vegetative parts of the oil palm on five different soil series; (b) mean concentration of potassium in the vegetative parts of the oil palms on the five soil series

Palm components	Selangor series (Typic Tropaquept) (15.5 years)		Briah series (Typic Tropaquept) (19 years)		Munchong series (Tropheptic Haplorthox) (16 years)		Kuantan series (Haplic Acrorthox) (12.5 years)		Malacca series (Typic Gibbsiorthox) (13.5 years)	
	Control	Manured	Control	Manured	Control	Manured	Control	Manured	Control	Manured
(a) Total K (g/palm)										
Pinnae	451	475	305	419	203	589	254	478	296	611
Rachis	923	1,170	696	1,019	192	1,062	311	857	335	1,029
Petiole	871	706	584	808	130	1,043	283	668	242	726
Frond bases	1,945	2,666	— ^a	— ^a	799	3,012	875	2,054	843	2,080
Trunk	4,745	7,117	7,221	11,236	1,241	5,453	2,373	4,965	739	2,864
Roots	717	744	617	734	730	954	263	381	452	639
Total	9,652	12,878	9,423	14,216	3,295	12,113	4,359	9,403	2,907	7,949
(without frond bases)										
Range	430	2,933	582	496	203	1,776	1,087	792	958	1,195
(+ from mean)										
Mean (increase/year)	623	832	496	748	206	757	349	752	215	589
(b) Mean K concentration (% in DM)										
Pinnae	0.73	0.94	0.73	0.75	0.57	0.91	0.73	1.08	0.76	1.08
Rachis	1.59	2.32	2.04	1.81	0.47	1.57	0.77	1.43	0.64	1.41
Petiole	1.63	2.22	2.39	1.93	0.46	1.92	0.98	1.76	0.77	1.38
Frond base	1.66	1.68	— ^a	— ^a	0.53	1.54	0.80	1.12	0.59	1.34
Trunk	1.35	2.33	2.01	1.85	0.36	1.40	0.92	1.53	0.34	1.19
Roots	0.79	0.79	0.75	0.82	0.46	0.82	0.46	0.76	0.53	0.85
Whole palm	1.32	1.86	1.74	1.67	0.44	1.36	0.83	1.34	0.51	1.22
Range (+ from mean)	0.25	0.20	0.02	0.09	0.17	0.12	0.24	0.01	0.15	0.08

After Teoh and Chew (1988b).

^aFrond bases have dropped off before 19 years.

per unit length of root (e.g. mol/cm per second) (Nye and Tinker, 1977; Tinker and Nye, 2000).

The structure and distribution of the root system, the controls on nutrient uptake and root–soil relations in general are described by Tinker and Nye (2000), and root nutritional physiology is described in detail by Marschner (1995). Much progress in research has been made since the 1970s, although much remains to be discovered. Root research has always lagged behind that on the shoot of the plant, largely because of the physical difficulty of access and experimentation with roots.

The anatomy of the cross-section of the palm root is fairly typical, and is described in Chapter 2. As it is a monocotyledonous plant, the oil palm has no tap root, but many (several thousand in mature palms) main axes that develop from the thickened bole at the bottom of the trunk, and that form the main rooting framework. These roots have no secondary thickening. The general pattern

has been known for a long time (von Mohl, 1849; Purvis, 1956), and subsequent researchers have always agreed that there are four main classes. Of these, the fine quaternary roots may or may not appear on a particular tertiary root (Fig. 11.5) (Jourdan and Rey, 1996). There are no reports of root hairs. The primary roots are 6–10 mm in diameter; these carry secondary roots (2–4 mm), which in turn carry branched tertiaries (0.7–1.2 mm) and then quaternaries (0.1–0.3 mm diameter, and 1–4 mm long) (Tinker, 1976). There is a clear spatial distinction between the main axes that penetrate more or less vertically downwards, and those that develop horizontally (Jourdan C., pers. comm.). The horizontal main axes then develop a few secondaries that either penetrate vertically downwards, or go vertically upwards until they reach close to the soil surface and branch extensively there to produce a dense mat of roots in the topsoil. The branches normally appear at right angles to the subtending root. The descending roots produce few tertiaries and secondaries.

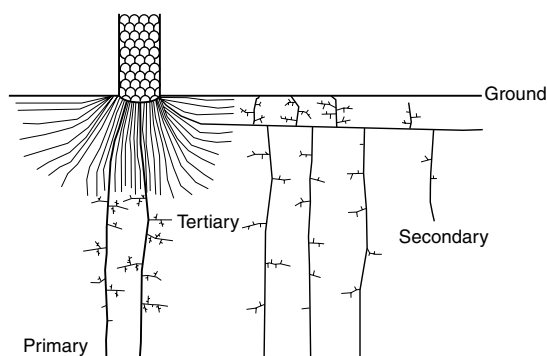


Fig. 11.5 Diagram of the principal parts of the oil palm root system, with root types. (After Jourdan and Rey, 1996.)

11.2.1.2 Quantity and position of oil palm root

The latest and most complete review of methods for measuring root length and weight is by Atkinson and Mackie-Dawson (2001). Most of the difficulties of working with roots arise from the problems of accurate measurement. Hertel and Leuschner (2002) compared four different ways of measuring fine tree roots in soil and showed that the results differed widely. The coring method, with careful washing out and measuring of roots, is almost certainly the most reliable. Tinker (1976) reviewed the work on oil palms up to that date, and reported data on weight and length (Table 11.6).

Table 11.6 Dry weight and lengths of roots of palms on coastal soil in Malaysia

Palm age (years)	Total dry weight of roots (kg/palm)			Estimated total length of roots (m/palm)				Total length/palm (km)
	Primary	Secondary	Tertiary and quaternary	Primary	Secondary	Tertiary	Quaternary	
1.5	3.8	3.1	1.2	530	2,540	5,820	16,150	25.04
2.5	8.1	6.2	1.8	1,130	4,030	8,730	24,230	38.12
4.5	19.1	12.5	4.9	2,660	7,460	16,220	45,010	71.35
6.5	28.1	9.0	3.5	3,920	3,690	11,580	32,130	51.32
8.5	25.7	14.1	4.3					
10.5	33.4	11.5	4.1					
14.5	48.7	15.8	4.4					
17.5	44.1	14.2	3.2					
27.5	90.4	30.3	10.1					

After Tinker (1976).

Gray (1969) estimated that the total length of root was about 70 km for a 4–6-year-old palm. However, the mass appeared to be only about 36 kg/palm, or less on unfavourable soils, which is about 5 t/ha. This is less than most recent estimates, which are given in Chapter 4 (see Section 4.1.2.3). The range was from 6 to 31.5 t/ha, but most results were around 10–15 t/ha dry matter. In recent work Khalid *et al.* (1999a, c) found 16 t/ha of root dry matter on palms whose shoots weighed 85 t/ha giving a root/shoot ratio of 0.19.

All of the palms were mature (>10 years), and according to Purvis the root weights of adult palms remained fairly constant. There is a possibility that the root weight differed on different soil types, but the methods used and the size of the palms may have differed also. The root weights on plinthic soil were less than half the estimates on better soils (Tan, 1979). It is unclear whether this is caused by damage to the root system in these soils, which then causes poor growth, or another effect that causes the plant to grow poorly, and therefore have a small root system. It would be useful if an estimate was always made of the palm shoot weight at the same time as the root is measured, because information on the root/shoot ratio is meagre. If the root weight remains constant while the shoot weight increases steadily with age, the shoot/root ratio must decline markedly.

Much of the root lies close to the surface, with most of the fine root in the top layer, down to 10–30 cm, the last figure varying with the study. However, Purvis (1956) noted that some secondaries went down below 1.5 m, which was the maximum depth that he investigated. In very deep sandy soils such as the West African acid sands, with a fairly constant clay content with depth, excavations or deep cuttings often show oil palm roots down to at least 10 m. Some work in Nigeria indicated uptake of radioactive phosphorus from 5 m depth (Forde, 1963, 1972). Ruer (1967a) also found considerable penetration to depth. Sommer *et al.* (2000) measured rooting depths on oil palms in the Amazon as 4.5 m, a little less than the rooting depth of primary and secondary forest. However, Lambourne (1935) found very few roots below a water table at 90 cm. Tinker (1976) calculated that the length of absorbing root (quaternaries and tertiaries) was about 60 km/palm, about 9000 km/ha, or about 0.9 km/m² land surface, based on a weight of 14 t/ha, and this estimate still seems to be the best available. This length may look impressive, but the amount of root under a large wheat crop is some 30 km/m² and, like all trees, the oil palm has a rather sparse root system compared with annual crops (Tinker and Nye, 2000). This is almost certainly connected to the need for the annual crop to complete its nutrient

acquisition in a relatively very short time compared with a perennial.

The most useful root parameter is root length density (m/m³) distribution around the palm, from which uptake processes can be modelled. In other circumstances the root length per unit land surface area (m/m²) is a better measure of the absorbing properties of the root system of a whole plantation.

Modelling of root architecture is developing rapidly (Lynch and Nielsen, 1996). There are now claims that root modelling can be applied successfully in the field (Dunbabin *et al.*, 2002). In this work the rooting patterns, water contents and nitrate contents in different parts of the profile of lupins was modelled, and found to agree well with observations. The results showed that local nitrate leaching was inversely proportional to the root length density, so that the rooting pattern could affect the total nitrate leaching. This morphological approach has been developed in great detail by Jourdan and Rey (1996, 1997a–c) (Figs 11.6, 11.7), based on fieldwork with minirhizotrons and trenching in the Ivory Coast, and computer modelling of root systems. They defined eight different root classes, including the direction of growth (horizontal or vertical) as a new criterion, and divided roots into four woody and four non-woody types. They made a detailed digital model of the root system, and computed that the total dry root mass increased from 0.02 t/ha dry matter at the seedling stage to 3 t/ha at 4 years and 55 t/ha at 16 years. This last figure is well above any published field measurement.

Little research has been done on the environmental relations of palm roots. Agamuthu and Broughton (1986) found that in flowing nutrient solution culture the maximum temperature for root weight, number and surface area was about 35°C. They also found that root development in soil was increased by nitrogen fertiliser up to an intermediate rate in roughly the same way as the shoots, but the results were very irregular. High rates of ammonium sulphate were detrimental.

11.2.1.3 Root systems and nutrients

The output from this simulation, based on field observations, was mainly in terms of biomass rather than root length. It showed that the surface horizons were well colonised by absorbing roots after 5 years, based on Purvis' (1956) assumption that quaternary and tertiary roots absorbed nutrients, but secondary and primary roots did not. In this case the absorbing root was 82% of total length. Alternatively, they used proton excretion on the root surface as an indication of root uptake

activity, which seems unlikely to be correct, because of the causes of proton excretion (Marschner, 1995). According to this measurement 23% of the whole root system length was absorbing. They also calculated the fraction of the soil from which phosphorus and potassium could be absorbed, based on the assumed mobility of these ions. These fractions were quite small at $33.4\text{ m}^3/\text{ha}$ for P and $235\text{ m}^3/\text{ha}$ for K; the latter corresponds to a layer of soil only 2.35 cm deep over the whole surface. Whereas these methods may give a very rough idea of the exploitation of the soil, it is not possible to set precise distances from within which roots can absorb nutrients, because diffusion is a time-dependent process (Barber, 1995; Tinker and Nye, 2000).

These modelling methods are mathematically very powerful, but their value depends on the accuracy of field measurements and the quantitative understanding of the important processes. At present, these simulated data do not include root length density ($\text{m roots}/\text{m}^3$ soil), which is the most important uptake parameter (Barber, 1995; Tinker and Nye, 2000). Since there is as yet no firm knowledge of the properties of different root classes, detailed information about distribution of these is at present of little value. From these models it should be possible to obtain data on root length density (Jourdan

and Rey, 1997a, b), and they provide good visualisations of general distribution.

The sharp distinction between descending and horizontal main axes appears to be a consistent feature of the palm root system in this work, which is not contradicted elsewhere. This suggests that the liminal angles of main axes descending into the soil cluster around 0° or 90° , so that the full root system is visibly bimodal (Figs 11.6 and 11.7). If so, then there are large volumes of subsoil midway between the palms that are very sparsely populated by roots. This raises questions of whether the root density there is sufficient to extract water and nitrate down to several metres (see Section 3.4.3.1), and suggests that more examination of this feature is needed. Schroth *et al.* (2000) found strong patterns of nitrate in the top 2 m of the soil, suggesting preferential uptake near the 15-year-old palms growing in a soil with high nitrogen content. This supports the idea of poor development of subsoil roots in the spaces between palms, as suggested above.

There is, however, a query over these morphological results. The palms had received fertiliser in the weeded ring around the palm (C. Jourdan, pers. comm.), and other work (Kee *et al.*, 1995c) has shown that after several years, the soil composition there will be very different to the soil elsewhere (Section 11.9.3). This may have an

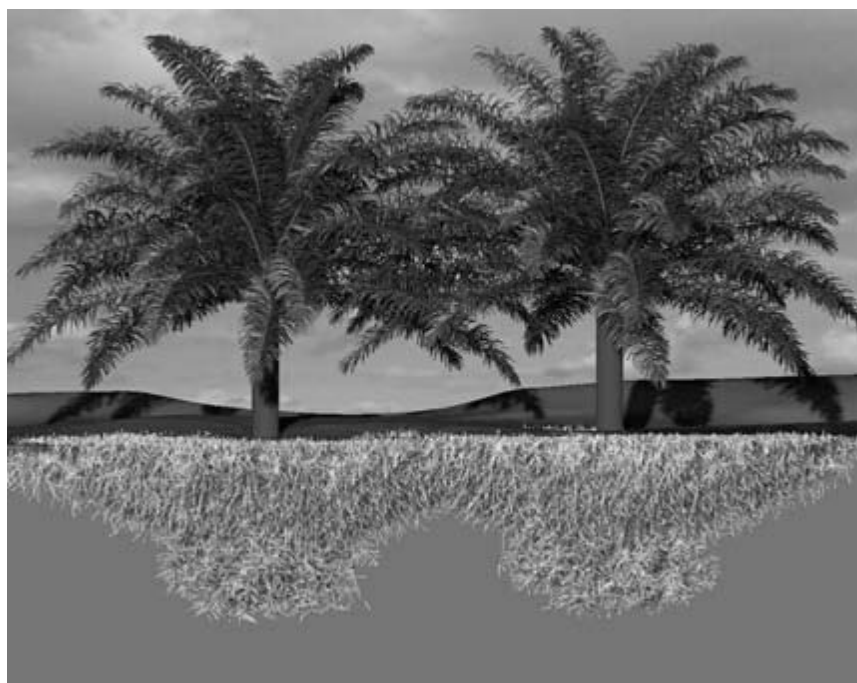


Fig. 11.6 Simulated distribution of roots under oil palms 11 years old, 9 m apart. Only primary and secondary roots are shown. (After Jourdan and Rey, 1996.)

effect on root development, and data are needed for palms growing in soil that has been uniformly fertilised, or not fertilised at all, to determine their natural behaviour.

Isenmila (1993) tested the effects of placing fertiliser at 30, 60 and 90 cm depths below the surface, 60–90 cm and 150–180 cm away from the trunk. Root proliferation was increased considerably near the placed fertiliser at depths down to 120 cm, as is found in most crops plants, and the rate of evapotranspiration during the dry season was increased where fertiliser was placed at increasing depths. Fertiliser placement may therefore be important in areas with dry seasons, but more work on this is needed (Table 11.7).

Palm roots penetrate a long way horizontally from the palm; thus, Ballo *et al.* (1995) showed by observations on poaching that significant nutrient uptake could take place beyond two palm rows away (*c.* 15 m). Zaharah *et al.* (1989) found uptake of placed labelled phosphate up to 35 m away. The simulations show a rapidly decreasing density away from the palm trunk (Fig. 11.7) (Jourdan and Rey, 1996). Fadli *et al.* (2002) placed radioactive phosphate at different distances from the trunk and depths in the soil. Despite some doubts about the dependability of this technique, their finding that more ^{32}P was absorbed when placed at 1.5 m than

2.5 m from the trunk agrees with root observations. One may therefore visualise the roots in the surface soil of a mature plantation as forming a widespread mat down to 50 cm or so, but with high density closely around each palm (Fig. 11.7). This is an important issue in relation to fertiliser distribution (Section 11.9.2.2), and more information is needed on how soon complete exploitation of the soil occurs on different soil types. Ruer (1967a) reported that *Deli duras* had a smaller weight of roots than interorigin *teneras*, and that root production was greatest under local accumulations of plant material (Table 11.7) (Tinker, 1976).

There is observational evidence that root systems die off in long dry periods, and root turnover may carry on throughout the palm's life, as happens in other species (Tinker and Nye, 2000). The work of Forde (1972) with radioactive phosphorus also supports this. Jourdan and Rey's (1996, 1997c) simulations suggest that self-pruning increases rapidly with age (Table 11.8), so that in the fourth year 82% of the root mass was lost. There are also effects of excessive water. Peralta *et al.* (1985) found primary and secondary roots weights to be fairly similar in well-drained and poorly drained soil in Costa Rica, but there was twice as much tertiary root in poorly drained as in well-drained soil, and the difference was most marked in the top 30 cm.

Table 11.7 Weight of roots

(a) Variation of root weight (kg dry weight/palm), to a depth of 90 cm, with distance from the palm trunk

Soil	Distance from palm (m)				
	0–1.2	1.2–2.4	2.4–3.6	3.6–4.8	Total
Shale derived, no concretions	17.6	8.2	7.3	5.8	38.9
Shale derived, few concretions	11.4	2.9	1.5	0.5	16.3
Shale derived, concretionary	10.5	4.1	0	0	14.6
Coastal clay	7.2	9.6	10.0	9.6	36.4

After Tan (1973) and Gray (1969).

(b) Weight of tertiary and quaternary roots (g dry weight/m² surface) in planting line and in windrow line, on two soil types

	Planting line	Windrow
Alluvial soil	34.9	60.1
Concretionary soil	52.7	64.5

After Tailliez (1971).

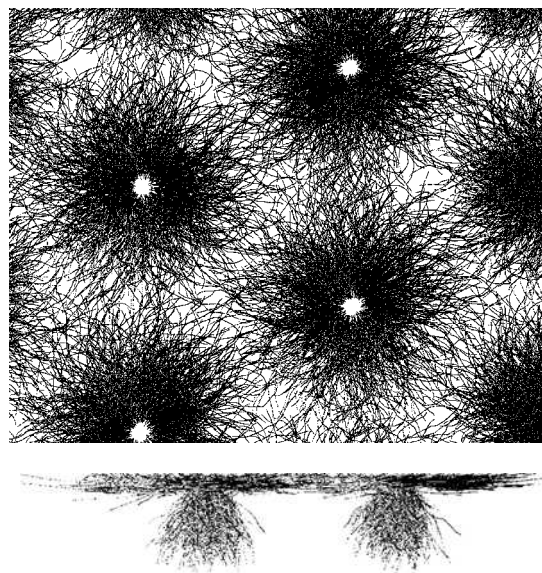


Fig. 11.7 Simulated distribution of roots in a 7-year-old plantation, as seen from above and from the side. Note that interpalm competition occurs only in the top soil horizon. (After Jourdan and Rey, 1996.)

Table 11.8 Simulated root mass produced and amount lost by normal dieback (self-pruning), in the first 4 years of an oil palm's life

Years since germination	Annual root biomass (kg)		Total root biomass (kg)	
	Without self-pruning	Self-pruned	Without self-pruning	Self-pruned
1	0.17 (–)	0.05 (29.4%)	0.17	0.05
2	3.65 (+2047%)	0.88 (24.1%)	3.82	0.93
3	18.42 (+405%)	11.14 (60.5%)	22.24	12.07
4	54.74 (+197%)	44.08 (80.5%)	76.98	56.15

After Jourdan and Rey (1996).

11.2.1.4 Root carbon demand

Several authors have measured the total mass of the roots (see Section 4.1.2.3). A carbon supply is required for root metabolism, for growing root that simply replaces dying root in root turnover, or root that extends the length and mass of the root system, and root that supports mycorrhizae, root exudation, etc. (Tinker and Nye, 2000). Whereas the measurement of the weight or length of the standing crop of roots is simply tedious, the estimation of the dynamics of formation and death of fine root is very difficult (Tinker and Nye, 2000). It is possible to measure the amount of carbon dioxide emerging from the soil surface, as a measure of the total carbon flux from the soil and roots. This must, in a stable system, be roughly equal to the amount passed down to the roots inside the palm and supplied to the surface soil by litter. However, this is a very complex system, and there are many involved questions concerning origins and pathways. Dufrene (1989), as reported in Jourdan and Rey (1996), found that about 36% of total assimilate production was translocated to the roots. This is a reasonable value compared with estimates for other tree species, and quite low compared to some tree species (Tinker and Nye, 2000; Hertel and Leuschner, 2002). The full discussion of this subject is in Chapter 4 (see Section 4.2.1.4).

These results suggest that root mass is much less in Asia than in the seasonal climates of West Africa. Henson and Chai (1997) found that only 4.5 t dry matter/ha per year is used by the root system. Bearing in mind that the total annual dry matter above-ground production of good mature palms in Asia is up to 45 t dry matter/ha (Chapter 4; Table 4.4), this is a remarkably small fraction of total dry matter going below ground, and well below that measured in various trees, where many published data suggest that the allocation below ground is 40–60% of the total fixed carbon (Tinker and Nye, 2000, pp. 230–231). These are very difficult measurements to

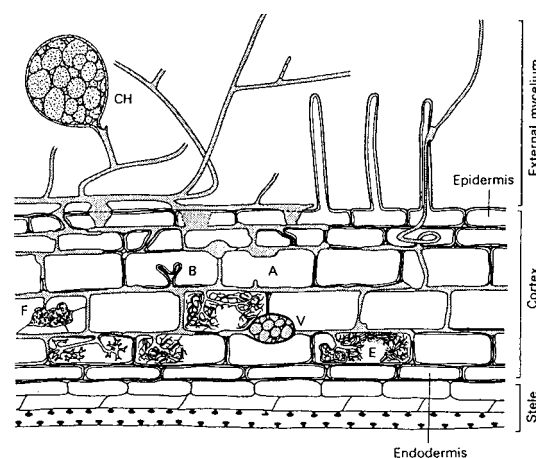


Fig. 11.8 Diagram of the morphology of an arbuscular mycorrhizal infection, showing internal and external mycelium. V: vesicles; A, B, E, F: arbuscules; CH: external spores. (After Tinker and Nye, 2000.)

make, but if these data are correct, they indicate that the oil palm root system is remarkably efficient in absorbing all of its water and nutrients for a cost of only 10% of its shoot dry weight.

11.2.2 Mycorrhizal infection

It is well known that oil palm roots in the field are infected with the endophytic arbuscular mycorrhizal (AM) fungi (Morton, 1942; Nadarajah, 1980; Moawad and Vlek, 1998). These fungi are widely distributed and infect the great majority of the world's vegetation (Smith and Read, 1997; Tinker and Nye, 2000, p. 194). It may be assumed that all experimentation in field soil will have been done with infected palms (Fig. 11.8). The most important practical function of these fungi is that they can absorb phosphorus and some trace elements from the soil and deliver them to the host root at inflow rates much higher than those at which the roots them-

selves can absorb (Tinker and Nye, 2000), thus relieving a deficiency of that nutrient. It is probable that oil palms are functionally dependent on the fungi, because clonal seedlings rooted out in sterile soil will not thrive unless they are infected. This may be done easily by adding a small amount of almost any natural soil, preferably one that has carried oil palms, although the fungi are not specific to particular hosts (Corley, 1993).

At present, there is little that can be done in practice to use mycorrhizal infection more effectively. The fungi are rarely host specific and all of the major strains are distributed very widely. All of the strains and species currently used as inocula have been isolated from wild or crop plants. The AM fungi cannot be caused to propagate sexually, and so far molecular techniques have not produced genetically new material. Artificial inoculation thus usually means using natural strains and species that are probably already infecting the crop naturally, and hence there is no benefit. This is very different to the situation with the ectomycorrhizal temperate forest trees, where the fungi are highly specific. In several cases the introduction of a specific fungus has proved essential for good growth of an exotic tree, although the underlying growth-enhancing process in the two forms of fungi may be similar (Tinker *et al.*, 1992). At present, the only practical use of the AM fungi is in artificial situations where potential host plants are being grown in sterilised soil or other media. They may prove useful in establishing clonal seedlings in soil. Widiastuti *et al.* (1998) found that palm seedlings growing in sterilised soil required much less phosphorus fertiliser if they were inoculated with *Gigaspora margarita* or other fungal strains. Smith and Read (1997) listed the agricultural conditions that reduce the inoculum density of AM fungi, and these may be candidates for artificial inoculation. The endophytes in some of the special soils used for oil palms, such as peats and acid sulfate soils, could usefully be investigated. The claim by Raja *et al.* (1999) that arbuscular mycorrhizal inoculum prolonged the productivity of *Ganoderma*-infected palms needs further testing. If confirmed, it would be very important.

11.2.3 Rhizosphere relations of the oil palm

Virtually nothing has been published on this subject except for issues of root disease (see Chapter 12). There is a wide range of questions that will have to be answered in due course (Amir *et al.*, 2001). The length of fungal hyphae is usually much larger than the length of the host root with which they are connected, and the frac-

Table 11.9 Mean inflow values for major elements into palm roots, compared with typical annual crop values

	N	P	K	Mg
Oil palm	4	0.25	2	0.6
Typical values for annual crops	10–15	1	5–10	–

All values are mol/cm per second $\times 10^{-13}$
After Tinker (1976).

tion of the phosphorus that is taken up via the endophytes needs to be measured, as has been done for other crops. The possibility of using rhizosphere growth-promoting bacteria should be borne in mind, although so far proposed uses have been disappointing (Kapulnik, 1996; Tinker and Nye, 2000, p. 193).

Some calculations have been possible on the nutrient fluxes in the rhizosphere (Tinker, 1973, 1976) (Table 11.9). Based on nutrient uptakes in Malaysia, and average root lengths for quaternaries and tertiaries, the maximum inflow values into oil palm roots were calculated; they are well below those into rapidly growing young annual crops. The latter would generally have root hairs, which make a very big difference (Jungk, 2001). This is largely because it is assumed that uptake continues around the year, and it would not be true for palms growing with highly seasonal rainfall. The implication is that the oil palm in a well-watered situation, with relatively fertile soils, could readily take up the nutrients needed. However, it is possible to calculate very approximately the minimum concentration that is needed in the soil solution to allow the measured mean inflow to occur. These are K (0.7×10^{-4}), P (3×10^{-6}) and Mg (1.5×10^{-5}), all in mol/litre. These values are not high for cultivated and manured soils, but they are quite high for most tropical soils that are not fertilised. It is not surprising that palms need consistent and quite heavy fertilising. The phosphorus need in the field is less than might be expected from these results, presumably owing to the mycorrhizal symbiosis.

11.3 NUTRIENT DEFICIENCY AND ITS CONTROL: FIELD EXPERIMENTS

11.3.1 Field experimentation: mathematical expression and treatment

This is discussed first because field experiments are the essential underlying check on all other methods. The fundamental measure of optimum nutrition is to test the way in which the plant reacts if more of a nutrient is

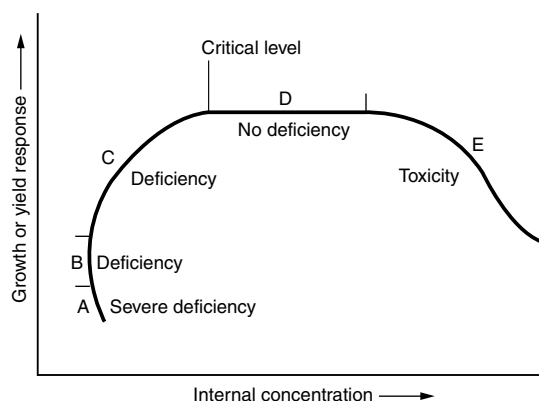


Fig. 11.9 Schematic diagram of relation between growth and yield, and the internal concentration of nutrients in a plant. (After Hartley, 1988.)

supplied. If growth and yield increase, the element is deficient; if they remain constant, the plant has a sufficient level, and if they decrease, the nutrient concentration of the element is toxic (Fig. 11.9) (Marschner, 1995). This shows the expected general responses to nutrient addition, with micronutrients most likely to produce toxic effects at high levels. However, Foster (2002) has stated that there is no luxury uptake in oil palms, which raises the question of whether this diagram is applicable to palms. The best practical field measure of the extent of a deficiency is the gain of growth or yield when ample nutrient is supplied, expressed as a percentage of the maximum non-deficient yield in the given conditions (Fig. 11.10) (Bray, 1954; AAR, 1999). This is different to the usual method of presentation, where gains are plotted as absolute amounts, or as percentages taking the current state arbitrarily as 100%. Figure 11.10 shows how the response curve changes as P builds up in the soil.

The relation between yield and soil nutrient supply can be expressed mathematically or graphically in various ways (Tinker and Nye, 2000). The simplest is as a rapidly rising line, followed by a long plateau, sometimes called the broken-stick model (Equation 11.3a) (Fig. 11.11a) (Tinker and Nye, 2000). This can be used in fundamental (Tinker and Nye, 2000) or in practical work (Boyd *et al.*, 1970), and is sometimes surprisingly accurate. Alternatives are the Mitscherlich equation (Russell, 1973; Caliman *et al.*, 1994; Marschner, 1995, p. 184) (Equation 11.3b; Fig. 11.11b). The inaccuracies of this model are discussed by Marschner (1995). This is effectively the same as the exponential equation as used by Foster *et al.* (1993) (Equation 11.3b). A polynomial (of which the quadratic is most popular) has also often been used (Foster *et al.*, 1985b) (Equation

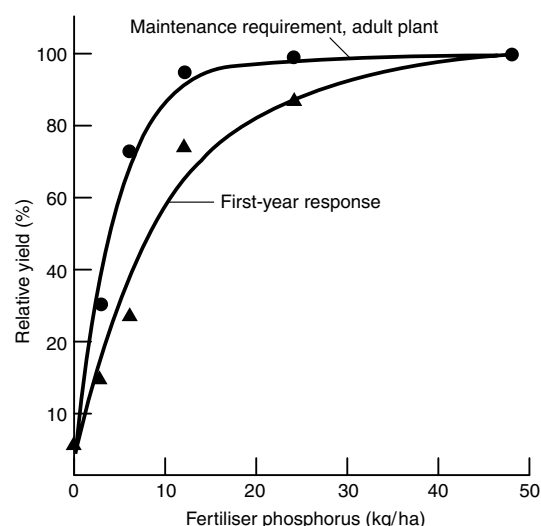


Fig. 11.10 Representation of response to fertilisers using a fully nutrient-supplied plant as the standard. (After Bray, 1954.)

11.3c; Fig. 11.11c). In single-plant work a form of the Michaelis–Menten equation may be used (Equation 11.3d) (Fig. 11.11d). It is not normally used for field results, but is included here to show how many mathematical expressions can give reasonable fits to the data. None of these is fundamental or exact, all being empirically based attempts to express a wide range of conditions in a simple form. The supply of nutrients from a field soil to a growing plant is a very complicated process, and it would be remarkable if it could be expressed simply and accurately. The reason for emphasising this point is that fitting any set of field data to one of these equations involves an assumption, which may force the data into forms that allow unjustified conclusions to be made.

$$Y = a + bX \quad \text{for } X < X(c) \quad (11.3a)$$

$$Y = Y_{\max} \quad \text{for } X > X(c)$$

$$dY/dX = c(a - Y) \quad (11.3b)$$

$$Y = a + bX + cX^2 + \dots \quad (11.3c)$$

$$Y = a(X)/(c + dX) \quad (11.3d)$$

Here, Y is yield, X is nutrient supply in an appropriate measure, and other terms are constants.

Fertiliser research on many crops has often used statistical field experiment designs with only three levels of treatment. This causes two difficulties. First, it is often unclear on inspection whether the maximum (third) level has in fact produced the maximum yield response. To be sure of this, the highest two points should show

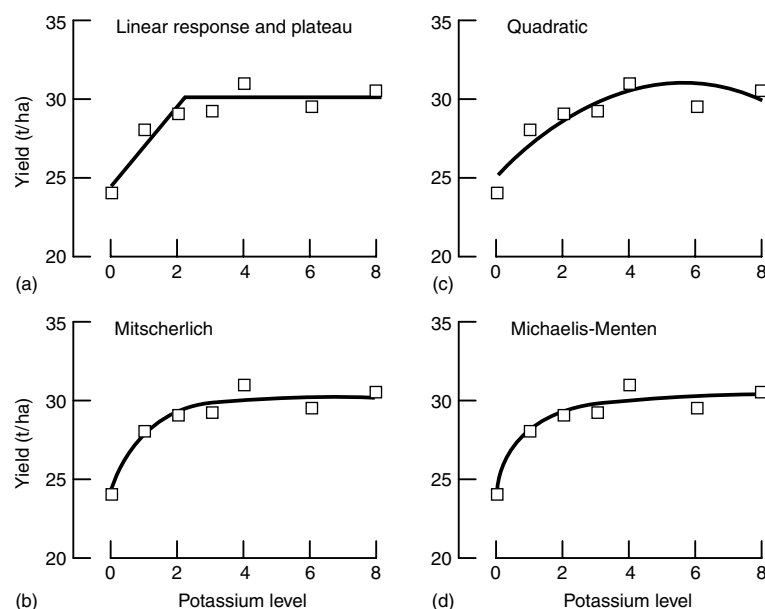


Fig. 11.11 Methods of representing the effect of nutrient supply level on yield and growth rate. (a) Straight-line model; (b) Mitscherlich exponential model; (c) quadratic (polynomial) model; (d) Michaelis-Menten model. (a) The linear response was fitted to the first three levels; the plateau is the mean for the four highest levels. The response function is: $Y = 24.5 + 2.62X$; (b) The Mitscherlich equation is: $Y = 30.3 - 6.21 \exp(-0.95X)$; (c) The quadratic equation is: $Y = 25.1 + 2.12X - 0.188X^2$; (d) The Michaelis-Menten equation is fitted to the yield minus control yield; yield without potassium was 24.05 t/ha, so the equation is: $Y - 24.05 = 7.3X/(0.74 + 1.04X)$.

Data points are from a 'non-random' potassium trial with seven treatment levels in Indonesia, from *Bah Lias Research Station Annual Report, 1992*; potassium levels are in kg KCl/palm.yr. Yields are mean FFB yields for 1989–1990.

equal yields, and if there are only three points in total, the rest of the curve must be very poorly defined. Secondly, it is always possible to fit a smooth curve to any three points on a graph. It is consequently very difficult to determine which mathematical function is most appropriate to express the response (Lo and Goh, 1973). A quadratic function has been very popular (Fig. 11.11c), but when used in this way it will normally rise to a maximum and then decline, possibly suggesting that the optimum rate of fertiliser is much more critical and well-defined than may be true (Boyd *et al.*, 1970). This argues the need to use at least four levels of a nutrient (Foong and Syed Sofi, 1988). This greatly increases the size of the trial, especially in a factorial experiment, but several palm experiments have used four or more levels.

11.3.2 Field experimentation practice

11.3.2.1 Practical considerations

The measure of a deficiency response as a percentage of the yield of a non-deficient plant can be calculated from field experiment results, given that sufficient rates of nutrient are tested to make absolutely sure that the maximum, non-deficient yield level has been reached. There are well-known practical difficulties in obtaining accurate data for this percentage response in the field, because of variable weather and many other problems of field experimentation. Because of the yield cycles of

the oil palm (see Section 4.5), it is normally necessary to run the experiment for at least 4 yielding years before accepting the results. The early years are particularly unreliable and variable, so definite values for a treatment effect may have to wait for 6 years from yielding starting in young plantings, and yield-determining events, such as droughts (Caliman and Southworth, 1998), other deficiencies or diseases, may have an influence for years into the future. For this reason, experiments are often laid down on a uniform field of mature but still young palms.

Good sites are not always easy to find, or are unavailable because of plantation policy. In particular, it may be difficult to gain estate commitment to a long-term experiment, without which much of its value will be lost. Sites should be representative in climate and soil of a relatively large area of a region. After the site is chosen, problems of soil or plant material heterogeneity cannot be corrected, and a selected statistical design is a permanent commitment that can only be altered with great difficulty.

Palm roots certainly travel further than a single inter-palm distance (Ballo *et al.*, 1995), and thereby raise the possibility of poaching on added fertiliser. Guard rows therefore have to be inserted between plots. Ideally, there should be at least two guard rows, one receiving each of the treatments applied to the neighbouring plots. Sometimes guard trenches have been dug between plots, to a width of ½ m and a depth of 1 m. This is better than nothing, but it disturbs root systems and

water relationships, and allows canopy competition to continue, and there is no guarantee that this is fully effective. Non-random designs of the experiments would allow the nutrient gradients between plots to be minimised, but they have rarely been used for oil palms except in density experiments (Goh, 1977) (but see caption of Fig. 11.11).

Palms are so large that only a small number of individuals can be included in a single plot. This tends to produce high plot errors for non-clonal material, and means that the death of one palm can only be dealt with by statistical corrections. The difficulties of field experimentation with large perennial plants are definitely greater than in annual crops. The theory and practice of oil palm fertiliser field experiments are still imprecise, but it is difficult to see how they can be greatly improved, or the cost can be reduced, until clonal planting material can be used as a routine. Nevertheless, they are the basic test of fertiliser use, and all other methods in essence extrapolate the results of field experiments. Visual symptoms, leaf analyses and soil analyses must all be measured against the results of well-run, statistically designed field experiments.

It is quite complicated to integrate the demand concept outlined here with normal field experiments. Consider an experiment that has been running for many years, so that the yields at each nutrient level are constant. Knowing the yield and growth, the growth plus environmental demands can be calculated for each fertiliser rate, and in the absence of complicating factors such as slow-release nutrients, this should be equal to the fertiliser rate. The information from the experiment is the size of the yield that a particular fertiliser rate gives at a steady state on this soil. However, the experiment in this steady state gives no information at all about the deficiency demand, which is needed if a field is to be raised from one yield level to a higher one.

Alternatively, consider a new experiment that is being laid out on a uniform and poorly fertilised field of palms. In this case, the higher rates will have to supply both the deficiency demand to raise the nutrient status, and also the increasing growth and environmental demands. The palm in effect finds a compromise path to reach a higher nutrient plane with a constant yield, after which the entire nutrient rate goes to growth demand. It is probably possible to calculate the deficiency demand at the various stages of this process, as the growth demand can be calculated from the FFB yield and the growth data, and the remainder of the fertiliser is deficiency demand. It is quite clear that the real information obtained from a field experiment depends very much on the local circumstances, and that this is not normally considered in using the data.

11.3.2.2 *Multiple nutrient trials and factorial designs*

Single-nutrient trials are tests of one fertiliser at one or more rates arranged in a randomised block or some other simple design. Where the question to be solved is which element is deficient, 'all minus one' trials may be used, in which all nutrients that could possibly be deficient are applied in one treatment, all the other treatments having one element removed from this base treatment. Both of these are valuable ways of gaining a rapid insight into the relative need for different nutrient elements, especially in areas where there is little basic information. However, at the next level of complexity it is necessary to determine the best levels of several nutrients simultaneously. In many cases Liebig's old 'principle of the limiting factor' is still surprisingly useful in relation to defining a need for several elements on a given area. This states (Russell, 1973) that in any one set of circumstances only one nutrient is restricting yield, and in the first instance only this will give a response. However, this does not mean that interactions between nutrients will not take place. After an increment of one element is added, perhaps a different element may become limiting, and when this is also added, the first may again become limiting. With incremental dressings of fair size, there may clearly be an interaction between the elements when both are added together, because the effect of one element depends on the presence or absence of the other. This is the essence of element balance, and can occur even when there is no definite physiological or biochemical interaction between the elements. This type of interaction is often found between nitrogen and water. In other cases there are well-defined physiological antagonisms or synergisms between elements, as with potassium and magnesium (Marschner, 1995), which will very often appear as interactions in multiple nutrient trials.

To determine practical fertiliser rates, several fertilisers are tested together in factorial experiments, in which several elements are present as treatments at several levels. In principle, a single replicate of the design combines all levels of all elements, even though in practice there are some statistical methods of reducing the plot number. The errors in such designs are often based on high-order interactions, which are assumed to be zero in reality. Hartley (1988, p. 526, 528) discussed some of the problems, and found that it was very rare in multiple factorials for more than two or three nutrients to give a significant response.

11.3.2.3 *Economics of applying fertiliser*

To fertilise for maximum profit is a more difficult task than simply detecting that a deficiency exists. The costs

of fertilising may be around one-third of the total cultivation costs of a plantation (Caliman *et al.*, 2001), although various estimates have been made. The total annual nutrient demands by Malaysian oil palms can be estimated (Ng *et al.*, 1999) to be 490 N, 60 P, 840 K and 150 Mg, all in thousand tonnes. They stated that the use of nutrients per unit amount of palm oil produced will be less for clonal palms, but there is little doubt that the total consumption of fertiliser will continue to increase.

Because fertiliser forms such a large part of the total costs of producing palm products, fertiliser rates will be under review whenever the industry is suffering from low product prices. The extremely low prices for palm in 2001, and the likelihood that the trend towards lower prices will continue (Fry, 1998; Stringfellow, 2000) (see Section 1.4.2), mean that the amount of fertiliser needs to be estimated with great care. Various approaches have been suggested for such situations, e.g. Caliman *et al.* (2001) suggested a strongly mathematical and precise approach, but it is doubtful whether this is useful at a time of financial stringency. In practice, fertiliser policy is often set by financial considerations rather than by scientific and technical knowledge. When the prices of oil and kernels are low, it is very tempting for management to cut the application of fertilisers, in the hope that prices will soon recover, and that the palms will not be affected by this deprivation. Some information on the immediate consequences of cessation of fertiliser can be found from the work on stopping fertilisers before a field is replanted (Nazeeb *et al.*, 1995; Teo *et al.*, 2000) (Section 8.3.4.3). These authors found that yield started to drop approximately 1 year after the last fertiliser application. The profitability of the application of fertilisers is usually so high that it is not sensible to cut fertiliser rates in this way if it risks losing yield. In such a situation it would be more useful, first, to review the nutrient cycle (Section 11.1.4) and ensure that the largest possible amounts of nutrient-containing wastes are returned economically. Secondly, it would be worth considering the most reliable available curve of the fertiliser response, and reduce fertiliser use by aiming for 80 or 90% of the most profitable yield rather than 100%. A planned but simple short-term saving can be made by approaching the problem rationally rather than by intuitive cutting for financial reasons (Tayeb Dolmat and Tarmizi Mohamed, 2001).

The estimation of fertiliser economics is simple in principle, but the perennial nature of the plant can cause problems. Fertilisers supplied to young palms may enhance the health and potential, and give a larger yield well into the future, which has not been well quantified. It is therefore advisable to continue a

fertiliser policy for several years, rather than amending it each year in line with oil, kernel and fertiliser prices. The cost of the fertiliser should be discounted into the future (Hew *et al.*, 1973), but the effects on future responses are not sufficiently well understood to make this fully accurate.

The net gain from 1 t of bunches is $V_{\text{net}} = a + b - c$, where a and b are the sale value of the oil and the kernels, respectively, and c is the additional costs in handling 1 t of FFB and its products, as in transport and mill costs. Then

$$\text{Profit} = GV_{\text{net}} - F + A + H \quad (11.4)$$

where G is the gain in yield/ha, and F and A are the purchase costs and the application costs of the fertiliser and H is extra harvesting costs. This is best considered as a simple graph (Fig. 11.12) (Tinker, 2001), with fertiliser rate plotted against fertiliser cost (including cost of application) and net gain in FFB value. If the cost line is transposed to be asymptotic to the response curve, this point is the rate at which a very small increase in fertiliser rate would equal the net gain in value, and where profit is maximised. The result is clearly very sensitive to the exact shape of the curve and hence to the choice of response equation (Eq. 11.3) (Section 11.3.1).

In all, it is praiseworthy to achieve a standard error per plot of better than 15%, as measured in plant breeding trials (Soh *et al.*, 1990), so that a response must be quite large to be significant. However, the cash value of small responses, say 5 or 6%, may be much larger than that of the fertiliser that gives the increase. The effect of a given fertiliser rate may therefore be non-significant in statistical terms, but profitable in economic terms, which sets a difficult managerial problem. This is particularly true if the palms are already giving a high yield, because

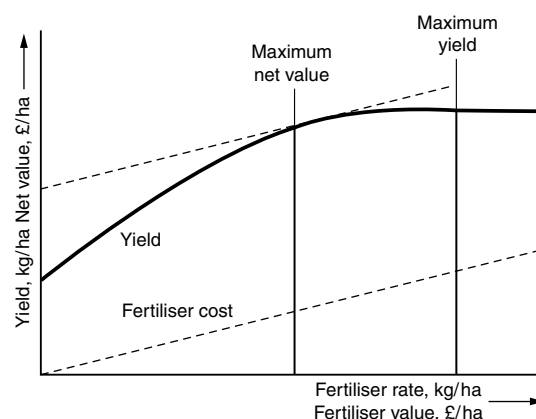


Fig. 11.12 Relationship between yield, fertiliser rate, fertiliser cost and net return (Tinker, 2001).

an absolute yield increase that is small in percentage terms may still be highly profitable. It is quite wrong to assume that because good yields are being obtained, additional fertiliser must be unprofitable. Almost any significant response in a high-yielding area will be profitable (Gunn, 1962), but the practical problem is how to deal with non-significant but economic responses; this may require that the usual standard of 5% probability has to be relaxed. The practical value of large field experiments is thus very dependent on minimising their errors.

It is worth bearing in mind that in virtually all cases a left-hand ascending limb of a fertiliser–response curve, in terms of net profit (Fig. 11.12), is steeper than a right-hand descending limb. Therefore, the results of underfertilising on the left-hand side, in terms of lost profit, are much larger than a similar error of overfertilising on the right-hand side. In practice, hardly any commercial field will achieve the ideal mean rate of fertiliser, and the field itself may be variable. The field experiments will have errors attached, as argued above, and the systems that transfer this information to determine the best rates on other similar fields (Section 11.6) will all contain errors. These can be from the practical measurements (leaf analysis or site characteristics) or from the statistically determined coefficients in equations. Even for fields on the same soil type, with the same planting material under the same climate, the response curves will vary, so that there is a large population of optimum rates of fertiliser. It can therefore be argued that it is better to overfertilise than to underfertilise, because of the asymmetry of risk. As far as we know, this aspect has not been calculated mathematically as yet. However, it is obvious that the more accurate the estimate of a fertiliser rate, the closer to that estimate should the actual application be made.

11.3.2.4 *Nutrients and bunch composition*

The results of field experiments are usually stated in terms of tonnes of FFB. However, nutrients can affect the percentage of oil and of kernels in fruit bunches, and so alter the economic value of fertilising. Corley (1973a) and Prabowo and Foster (1998) reported that applying potassium reduced the oil/bunch ratio through a decrease in the mesocarp/fruit ratio, in both Malaysia and Indonesia. A reduction in mesocarp/fruit was compensated by an increase in kernel weights (Foster *et al.*, 1988b). However, Foster *et al.* (1988b) found the opposite effect on Malaysian coastal soils, where potassium increased mesocarp/fruit. In all these experiments applied potassium increased FFB yield. There is also a small interaction with the leaflet magnesium level,

with a fairly small increase in mesocarp/fruit as the magnesium level in the leaves increased from 0.12 to 0.24% (Prabowo and Foster, 1998).

11.3.3 *Field experiment results*

11.3.3.1 *Early results*

Hartley (1988, p. 523) presented an excellent survey of early work on field experimentation. A good very early example of factorial trials were the Crowther experiments, laid down in the 1930s, on oil palms on Unilever plantations in Nigeria, the Cameroons and in the Congo (Haines and Benzian, 1956), which tested NPK, NPKMg or NPKMgCa fertilisers. At that time, there was doubt about the need for any fertilisers, which were then used quite sparingly even in agriculture in developed countries. Most areas were then planted following high forest, where the accumulated nutrients in the forest could support a plantation for some years. However, where later experiments could be conducted on existing unfertilised plantations, as in West Africa, the responses were often spectacular in percentage terms, but not in absolute terms, because of the low initial yields. Since then, programmes of experimentation have been carried out in all major oil palm-growing countries. The many factorial trials in Malaysia were organised by different private research organisations belonging to plantation companies (Chew *et al.*, 1998) and were later used for an integrated study by the Palm Oil Research Institute of Malaysia (PORIM) (Foster *et al.*, 1984b) (Section 11.6.4). In West Africa the Nigerian Institute for Oil Palm Research (NIFOR) laid down a number of large field fertiliser experiments in the 1950s and 1960s (Hartley, 1988), as did Institut de Recherches pour les Huiles et Oléagineux (IRHO) in the Ivory Coast and in many other areas (Caliman *et al.*, 1994). In Indonesia, series of trials have been reported by Tampubolon *et al.* (1990) and Foster and Prabowo (1996a, b). It soon became clear that on all normal soils some form of fertilising became necessary with time. There were also some specific requirements; thus, in the Belem area of Brazil there was an overriding shortage of phosphorus that had to be corrected at once (Pacheco *et al.*, 1985; Hartley, 1988). The conclusions were summarised by Hartley (1988).

11.3.3.2 *Regional results*

In the early years the amount of fertiliser applied in an experiment was largely chosen by guesswork. Furthermore, the yield levels at that time were much lower than now. This was especially true in west Africa, where a yield of 10 t of FFB on a research station was

regarded as very good. As palms are now planted on land with less existing chemical fertility, and the yields are much higher, it is scarcely surprising that the fertiliser requirement has grown rapidly, and no commercial plantation could afford to omit fertilisers.

A brief précis of the results of this large body of experimentation is given below, mainly based on Hartley (1988), Caliman *et al.* (1994), Rodrigues *et al.* (1997), Taryo-Adiwiganda and Poeloengan (1998) and a number of other authors from Malaysia and Indonesia.

- Potassium is needed on the sedimentary sandy soils of West Africa (Ochs *et al.*, 1991) and the sedimentary soils of Sumatra. Most inland soils in Malaysia need potassium, but coastal soils generally do not.
- Nitrogen is generally needed in the early years of a planting, and later on both the sedimentary and the volcanic soils of Sumatra and elsewhere in Indonesia if high yields are desired. The main fertiliser need in Papua New Guinea (PNG) is nitrogen, with potassium being the second (Oliver and King, 1996). On many sedimentary soils there is no response to nitrogen with adult palms.
- Phosphorus is needed on most sedentary and coastal soils in Malaysia, the basement complex-derived soils of West Africa, the volcanic soils of Sumatra and parts of the sedimentary basin of the Amazon in Brazil.
- Magnesium may be needed on acid highly desaturated sandy soils of West Africa, in the Amazonian part of Ecuador, and on poorer sandy soils in Malaysia and Indonesia.
- A need for calcium is very rare, or absent.
- Chloride is beneficial on alluvial and colluvial soils in Colombia, the Amazonian parts of Ecuador and Peru, and volcanic soils in PNG.
- Trace element deficiencies are occasionally found, but they are not often a major problem, except occasionally boron deficiency (Corrado *et al.*, 1992). Copper deficiency may be found in the Amazon basin and on peat soils in Asia, and zinc is needed on many of the latter.

Large fertiliser experiments continue to be conducted in South-east Asia, the main new aspect being in connection with the use of peat soils (Tayeb Dolmat *et al.*, 1996). There is a shortage of good experiments in Africa and South America.

The continued appearance of improved oil palm material suggests that it may be necessary to repeat fertiliser experiments periodically (Section 11.6.4.3). However, there is little evidence at present that this is needed, so long as the increased demand due to increased yields is allowed for. This conclusion may

Table 11.10 Differing concentrations of potassium and magnesium in different planting material growing on the same soils in three fields

	LMGP 70 (P 1985)		LMGP 71 (P 1985)		LMGP 76 (P 1986)	
	K	Mg	K	Mg	K	Mg
LMC 051	1.20	0.19	1.19	0.22	1.21	0.22
L2T × D10D	1.10	0.22	1.00	0.32	1.02	0.28

After Caliman *et al.* (1994). P = planting date.

need to be reconsidered as clonal material becomes more common. There are, however, differences in the leaf composition with different plant materials (Tan and Rajaratnam, 1978) that need to be considered when using leaf analysis. Caliman *et al.* (1994) refer to consistently different leaf concentrations of potassium or of magnesium in a standard cross and a clone (Table 11.10). However, this does not necessarily mean that the fertiliser need is different, simply that the critical leaf levels may need to be adjusted.

The response curve established in the field experiment, whatever the model used (Figs 11.11, 11.12), will not apply exactly to other fields, even within the same soil series, as their soil nutrient and carbon concentrations will almost certainly differ. The response curve will therefore vary in almost every field. Therefore, searches are made for means of extrapolating these results, using soil survey, climatic and general survey, yield levels, tissue nutrient concentrations or soil nutrient concentrations (Foster, 2002). Characterisation by soil series names is useful, but not dependable, because of the variation of characteristics within one series (Foster *et al.*, 1985b; Foster and Tarmizi Mohamad, 1988; Tarmizi Mohamad, 2000) and the big differences between series. The most general methods of extrapolating field experiment results are visual symptoms, tissue analysis (usually leaf analysis), soil analysis and nutrient balances. Each of these will be examined below.

11.4 NUTRIENT DEFICIENCY AND ITS CONTROL: VISUAL SYMPTOMS AND LEAF ANALYSIS

11.4.1 Visual symptoms of deficiency in oil palms

11.4.1.1 Visual symptoms as a guide

The determination of the best rate and type of fertiliser application is a critical problem in oil palm culture.

Various systems have been developed over the years. A recent survey of much work on leaf symptoms by PORIM has been given by Chan *et al.* (2000). The first approach is to determine whether the leaves show symptoms that from previous experience can be associated with a nutrient deficiency. The symptoms may have been produced in sand culture, to make sure that they are genuinely associated with a particular nutrient (Bull, 1961a, b), or they may have been cured in the field by applying a particular fertiliser. Alternatively, leaf painting or injection with a range of nutrients may remove the symptoms, or colorimetric methods applied to expressed sap can suggest which element is deficient (Bould *et al.*, 1983). These methods are now considered to be of uncertain and varying reliability; thus, strong magnesium deficiency symptoms can usually be recognised with confidence, but a pale general chlorosis may indicate one or more of several possible problems. A well-defined symptom usually indicates that a palm is suffering a severe deficiency, at a level that should not appear in any modern plantation: it is a lagging indicator rather than a leading one. As such, these methods are now of less importance than when the principles of the nutrient requirement of oil palms were still being sketched out. Any attempt to measure visual symptoms quantitatively is very difficult, and the linkage between the symptom and the amount of nutrient needed is very uncertain, so the symptoms give little guidance on the amount of fertiliser to apply. At one time it was regarded as sufficient success if the symptoms disappeared after a fertiliser treatment, but this did not guarantee that the application had given maximum yield, or that the amount of fertiliser had not been excessive.

11.4.1.2 Symptoms of potassium deficiency

A variety of symptoms has been associated with potassium deficiency in the mature oil palm in the field. At one time there was much speculation over the reasons for this variety (Bull, 1954, 1961a), but no clear conclusion was reached. The symptoms described below are normally found with potassium deficiency, but their appearance is often inconsistent and variable. The use of leaf symptoms gives indications rather than certain conclusions, and much time has been spent on attempting to reach an illusory certainty. In modern plantation practice one would not expect to see these symptoms frequently (IRHO, 1992a).

Early work was described by Hartley (1988, p. 485) and a more extensive description of these symptoms can be found there. These were largely on extremely deficient palms growing in sandy soils in West Africa, of mixed

and unknown parentage, and after poor and ill-defined growing conditions. Their symptoms were shown to be mainly associated with potassium deficiency, and were given various names, of which 'Confluent orange spotting' (Bull, 1954) was the most important. This consisted of pale green spots that gradually became more coloured through yellow to orange, and that simultaneously expanded both across and between veins, with fusion of these into larger irregular areas. Necrotic spots then appeared within the lesions, with possible fungus invasion. From a distance the palm has a 'bronzed' appearance. The same symptom has been found in Malaysia and Sumatra, but it appears somewhat irregularly. It is not a reliable indicator of potassium deficiency when it appears, and potassium deficiency may occur without confluent orange spotting. There is certainly a genetic factor that affects its appearance, and there may be an effect due to calcium status. Hartley (1988) lists a number of synonyms for this condition.

Other chlorotic conditions that have been associated with potassium deficiency are Mid-crown-yellowing, where the name describes the condition well (Plate XB, C). This chlorosis is a pale yellow, without the usual orange tints. It has only been found where the potassium concentration in leaf 17 falls below 0.3%. Another variant has been called Mbawsi symptom, from the Nigerian plot where it was first seen. This is characterised by large orange patches on leaflets, the central midrib and the margins of the leaflet remaining green. All these severe potassium deficiency symptoms include marginal necrosis on older leaves, and older leaves may die back completely, as potassium is recycled to the growing point. In seedlings palms grown in sand culture potassium deficiency symptoms are pale green to white interveinal mottling. Later the leaves become pale olive, and necrosis develops.

11.4.1.3 Symptoms of other deficiencies

Magnesium deficiency is the most easily and reliably recognised deficiency symptom (Dubos *et al.*, 1999), and used to be called Orange Frond. In severe cases the oldest leaves are dead, the next oldest a strong and striking orange colour (Plate IXC, D), then yellow, with the chlorosis decreasing towards the top of the palm. The necrotic areas of leaflet are brownish or purple, quite different from the clear grey withered areas on potassium deficient leaves. The youngest leaves are healthy. A very typical symptom is the shading effect, where the chlorosis is always strongest in full sunlight, and areas of leaflet shaded by another closely overlying leaflet will remain green. The same symptom has been reported

for Mid-Crown Yellowing. The effects in seedling palms are rather different, for example magnesium deficiency symptoms are yellow rather than orange.

With nitrogen deficiency there are some general effects in most crops. These are pale green or yellow-green leaves caused by lack of chlorophyll, occasionally with strong red or orange colours due to anthocyanins, and accelerated senescence (Bould *et al.*, 1983). In the oil palm a pale colour is the most usual symptom in young palms. In older palms the same colour appears, with a yellow or orange colour preceding leaf necrosis (Hartley, 1988) (Plate IXA). The pale colours are reversible, and when nitrogen is supplied the plant rapidly becomes green again. Nitrogen deficiency of this degree of severity is rare in well-managed plantations, except when there is flooding and waterlogging. Denitrification occurs in the anoxic soil, with resulting strong nitrogen deficiency symptoms. The symptoms may also be found in poor soils where competition by grasses has been allowed to develop.

Normal symptoms of phosphorus deficiency are seen as slow growth and some distortion of leaf habit. Deep red and purple colours occur in some plant species when the deficiency is serious (Bould *et al.*, 1983). In oil palms the effects are very rarely seen in the field, and the full expression is only found in sand culture. The leaves become olive-green in colour and a brown necrosis occurs around the edges. They are usually very small (Hartley, 1988).

Calcium deficiency has been produced in sand culture, showing malformed leaves and terminal necrosis, as is expected with an element that is not mobile in the phloem. It has never been seen in adult palms, and the requirement for calcium seems to be remarkably small.

Sulfur deficiency symptoms are very pale yellow or almost white leaves in seedlings, leading on to chlorosis. There seem to be no certain reports of the deficiency in adult palms.

The only chlorine deficiency symptom (11.4.5.1) to be reported is flaccid and olive-coloured leaves.

Boron deficiency has frequently been reported, though many reports have been uncertain. The symptoms in sand culture are always small leaves and short petioles. Rajaratnam (1972a) also reported the 'hook leaves' and the leaf corrugations that are characteristic of the deficiency in adult plants (Plate 11.1). The 'little leaf' symptom is quite general (Plates 11.2, 11.3), with much shortened leaves that may have malformations, but the term is used in various ways, and other pathogenic conditions that damage the growing point may produce rather similar effects. In adult palms the symptoms are hook leaves, with the points sharply



Plate 11.1 The 'hook-Leaf' condition, which is of wide-spread occurrence, seen in Ecuador (P.F. Arens).



Plate 11.2 Palm showing shortened leaves devoid of leaflets, probably through deficiency of boron (Malaysia).



Plate 11.3 A 'little leaf' with pronounced lamina condition.

bent (Plate 11.1), and corrugated, small and malformed leaves. These are all indicative of a non-mobile element whose absence in the growing point leads to abnormal development of new leaves (Corrado *et al.*, 1992). These symptoms are most likely to occur where soil boron is less than 0.3–0.5 ppm.

Iron deficiency must be very rare, with oil palms mainly growing on acid soils with much iron oxide. Again, in sand culture the symptoms are a pale chlorosis and necrosis.

Manganese deficiency has been found in the field (Kee *et al.* 1995a), where the soil level of manganese was extremely low. The palms were chlorotic with small and limp canopies. In seedlings there is a pale chlorotic striping, leading to necrosis.

Zinc deficiency is important, as it tends to occur on peat soils, where it has been called peat yellows (Plate XD). Gurmit (1988) described it in young palms as a yellow-orange chlorosis of the older fronds. Later young fronds become pale and chlorotic. Palms on field edges where they get more light are most strongly affected. Symptoms tend to appear about the time that palms are brought into bearing.

Copper deficiency also occurs on peat soils, and it has been reported as being serious on a sandy mineral soil (Wanasuria and Gales, 1990). The symptoms

(Turner, 1981) are called 'nursery white stripe', mainly on the younger leaves, with chlorosis and necrosis on the tips of young leaves. In adult palms frond shortening, chlorosis and necrosis occur on the young leaflets.

11.4.1.4 Remote sensing for plantation oversight

It is appropriate to consider here the use of remote sensing to identify mineral deficiencies in the palm, as a modern form of visual symptom observation. Lukman Fadli and Siahaan (1995) tested the use of SPOT images, which have a very good resolution, but are not always easily accessible. Nguyen *et al.* (1995) used this imagery to determine that palm areas with very different contents of N, P, K, Ca and Mg could be defined, with possible identification of boron and molybdenum deficiency. Naert *et al.* (1990) also used SPOT imagery to follow the appearance of the canopy in an Indonesian plantation where 8 ha plots had been laid out that had received all nutrients, or all omitting N, P, K or Mg, or no fertiliser. They found fair correlations between near infrared reflectance and the nutritional state of the leaves, including N ($r = 0.77$), P ($r = 0.77$), Mg ($r = 0.76$) and S ($r = 0.79$). This technique needs to be fully validated before it can be depended upon. Many claims of identification of environmental variables by remote sensing have been made, without the degree of accuracy and dependability being clear.

11.4.2 Plant composition

11.4.2.1 Plant composition and deficiency

The composition of a plant changes as it becomes deficient, and its growth rate declines. The classical schematic diagram relating growth to nutrient concentration in some plant tissue (leaves or other plant parts) is shown in Fig. 11.9 (Hartley, 1988, p. 497). Section A, with reversed slope, is known as the 'Steenbjerg effect', and may be found in severe deficiencies, but is often not seen. If it is true, as claimed by Foster and collaborators, that oil palms show no luxury uptake, then this classical curve would need to be altered, so that the concentration increased to a peak composition, but then remained constant (Section 11.6.4).

The mechanism that connects these two parameters is not always clear. The obvious explanation is that the lack of the necessary concentration of the element leads to slower photosynthesis in the leaves, lower free sugars and hence slower growth. However, the net photosynthetic rate is often found to be almost unchanged by the deficiency, so that there are ample soluble sugars in the plant, whereas the real effect of the deficiency is that

leaves grow and expand more slowly (Section 4.3.2) (Tinker and Nye, 2000, p. 278). The lower leaf area then leads to slower photosynthesis and growth. In other cases, the allocation of photosynthate is changed when a plant is deficient, producing alterations in the root/shoot ratio (Section 11.2.1) (Tinker and Nye, 2000), so that again the leaf area is reduced. The net result is always a reduction in growth rate, and vegetative and economic yield.

The lowest leaf (or other tissue) concentration at which the maximum yield is obtained is called the critical deficiency content (CDC), the critical concentration or the critical level. However, in practice, these terms sometimes refer to 90% or even 80% of the maximum yield or growth rate (Marschner, 1995). It is usually difficult to determine the point where the curves in Fig. 11.11 become horizontal, and the CDC depends greatly upon the mathematical model used to fit the data (Section 11.3.1). Critical levels can also differ depending on the duration of the deficiency, the age of the plants or many environmental factors (Ollagnier *et al.*, 1988; Foster *et al.*, 1988c) (Section 11.4.4). Critical levels thus depend on many plant and environmental variables (see Marschner, 1995, p. 464ff.), and there is no way of predicting them from basic physiology.

11.4.2.2 Composition of oil palm tissues

The most critical part of the leaf for growth is the cell cytoplasm, which is the living part of the cell, but only a small part of its volume or mass. This has a very stable elemental composition, that is linked to the much more variable concentration in the leaf vacuole (Leigh and Wyn Jones, 1984; Tinker and Leigh, 1985; Karley *et al.*, 2000) in a non-linear way, and has no well-defined relationship with the concentration in the cell wall, which is largely non-living, and has a disproportionately high concentration of adsorbed calcium. The concentration of the nutrient in the cell is therefore an average across that in the cytoplasm, the vacuole and the cell wall, so that the mean depends on the concentrations and on the relative weights of the three components. The concentration of the element in whole leaves depends on this mean concentration in the living cells of varying types and ages, and also on the relative quantity of dead cells, and on the much larger amounts of lignins and other non-living material. The overall concentration in the total leaf dry matter is therefore a very complicated value, with only an approximate relationship to that in the cytoplasm, and too much should not be expected of its properties as a criterion of the nutritional state (Tinker and Nye, 2000, p. 277).

It has been traditional to use the pinnae of the palm fronds for leaf analysis, probably based on the long history of leaf analysis in other crops (Bould *et al.*, 1983),

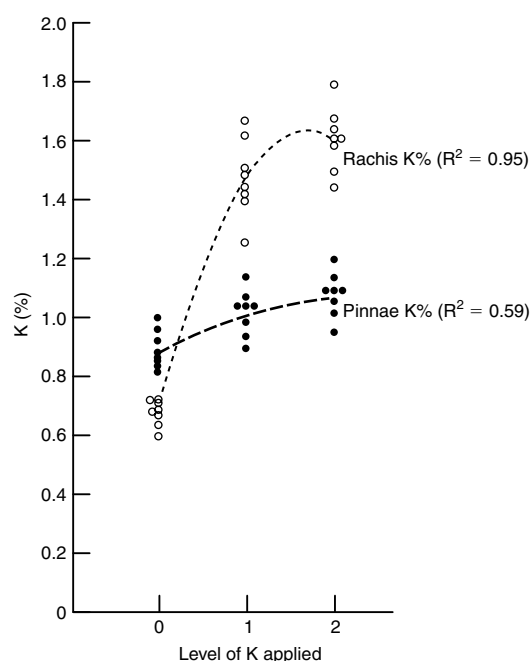


Fig. 11.13 Relationship of potassium in the rachis and the pinnae with the supply of potassium fertiliser. (After Teoh and Chew, 1988a.)

and the ease of access for sampling. Detailed directions on to how to do this on a routine basis are given in Rankine and Fairhurst (1998c). Hartley (1988, p. 496ff.) has given a detailed review of how the present system of leaf analysis evolved, and gave data on the accuracy of measurement of the various nutrients produced by the system then in greatest use. The variation is undoubtedly largest for the three cations potassium, magnesium and calcium, so that the errors in the results are largest for these, as the same samples are used for all elements.

However, leaves were selected as the tissue for analysis largely on the basis of convenience, and it is certainly possible that other tissues could be more sensitive to deficiency. The importance to the palm of having stable concentrations in the leaflets is obvious, and this quality may have developed over long periods. Palm trunk composition changes widely when deficiency appears (Tinker and Smilde, 1963b; Teoh and Chew, 1988a, b) (Table 11.5). Teoh and Chew (1988a, b) found that most of the plant potassium was in the trunk and rachises, and showed that potassium in the leaf rachis was very sensitive and had a closer relationship with applied potassium fertiliser than did leaf potassium (Fig. 11.13) (Teoh and Chew, 1988a). However, taking representative samples from palm trunks is not easy (Teoh and Chew, 1988b). There was a range from 0.5% K in rachises of

Table 11.11 Concentrations of phosphate and potassium in the leaves and the roots of palms that had or had not received these nutrient fertilisers, showing the larger changes in root than in leaf concentrations

% of dry matter	P			K		
	Without	With	Increase (%)	Without	With	Increase (%)
Leaf content	0.170	0.177	4	0.578	0.907	57
Root content	0.051	0.114	124	0.346	0.739	114

After Hartley (1988, p. 521).

unfertilised palms to 2.3% K in fertilised palm, whereas pinnae potassium ranged only from 0.6 to 1.1% K (Teoh and Chew, 1988a). However, this sensitivity did not lead to excessive random variation, as the coefficient of variation (CV) of rachis potassium for individual palms within the same treatment plots was 20%, only a little above the 15% often found in commercial leaf analysis. It is therefore possible to cut down the 17th frond, as for normal leaf analysis, and then take rachis samples, but it is still not as simple as leaf sampling. Foster and Prabowo (1996b) concluded that potassium status could be classified according to rachis analyses as high (>1.60%), adequate (1.31–1.60%), marginal (1.01–1.30%) and low (<1.01%), and some sampling in Indonesia now uses both rachis and pinnae (H.L. Foster, pers. comm.). Foster and Prabowo (2002) reported that yield responses to K were better correlated with rachis concentrations than with leaf concentrations. The poor correlation in the latter case were due to some very low leaf levels when rachis levels were high. However, addition of N fertiliser then significantly increased P and K in the leaves. Adding K could also increase leaf N. Optimal rachis levels were 0.091–0.113% P, 1.17–1.47% K and 0.073–0.114% Mg. The overall correlations of P and K in the rachis with the yield response were much better than the correlations for leaf concentrations, if other elements were not limiting. The correlation for leaf K was particularly poor, with R^2 of 30%. The improved result when other deficiencies had been eliminated is important. The authors have suggested a step-by-step series of observations, from which the most important deficiencies could be deduced successively, and corrected. These use both rachis (P and K) and leaf (N and Mg) analyses. This is very probably an improvement on current leaf analysis methods. However, the reason for these rather complicated interrelationships is not understood at a physiological level, and the method remains empirical, even if better than current methods. In some experiments the most profitable treatment was much less than the optimal (highest yield) treatment, which is unusual, and presumably indicates a very small slope of the response

curve. Finally, IRHO (1974) (Table 11.11) showed that the potassium and phosphorus concentrations of root samples doubled after treatment with fertilisers, while the leaf concentrations changed little. It thus seems certain that several tissue concentrations are more sensitive to the nutritional state of the palm than those in the pinnae, but this would be of little use if it led to results with larger errors. In practice, so much effort has been invested in developing leaf analysis as a practical tool that it seems unlikely that the industry will abandon it.

11.4.3 Leaf analysis in practice

The most general and practical way to determine deficiency has so far been to determine the concentration of nutrients in the leaves of palms in a fertiliser field experiment, sampled at standard times and in standard ways (Rankine and Fairhurst, 1998c; Fairhurst, 1998). This is tested for correlation with the yield response to that nutrient in field experiments to determine whether a relationship exists. If so, the state of deficiency in palms on any field can in principle be defined by leaf analysis. In practice, there are many problems, mainly due to different soil types and climates (Ollagnier *et al.*, 1988).

There are two types of answer desired from leaf analysis results. First, they could indicate whether the palms need fertiliser, and secondly, they could tell how much is required. The information on whether there is a deficiency is reasonably reliable, though by no means perfect. New systems continue to be proposed, such as DRIS (Walworth and Sumner, 1987, 1988) (see Table 11.24), which combines leaf analysis data in complicated ways to obtain a more reliable output. However, leaf analysis does not directly carry any information about the amount of the nutrient required annually by the plant, as in the growth demand. It can in principle give the deficiency demand, from the concentration of nutrient in the leaf if whole-palm concentrations can be inferred.

In this section leaf analysis is discussed mainly in terms of its ability to determine the existence of an

element deficiency; the related but more difficult problem of using it to design a practical system of fertilising is covered in Section 11.6. A field experiment will give useful guidance on the amount of fertiliser needed to raise the leaflet concentration to the CDC. The problem is that the soil solution concentration of a nutrient is the primary controller of the nutrient uptake rate, and this is not known. However, it might be possible to use the relationship between the soil solution concentration of a nutrient and the mean concentration of the available nutrient in the whole soil (the nutrient buffering power) to estimate approximately the amount of fertiliser required on a different soil, though we are not aware of this having been done. It remains very difficult to define the amount of fertiliser required for the deficiency demand simply on the basis of initial leaf analysis, but it may be possible to do so with a good knowledge of the soil properties and fertiliser experiment results (Section 11.6.4). Leaf analysis data can probably be used to estimate the growth demand (Section 11.1.4.3).

A slower method to reach the CDC condition is to add an estimated amount of fertiliser that will improve the nutrient status each year, over and above the growth demand, and monitor the leaf composition over several years until it reaches the acceptable level. At this point, the amount of fertiliser should be reassessed and the amount aimed at meeting the new growth demand only (Section 11.5.3). Teoh and Chew (1988b) pointed out that if palms were grossly deficient, it would take a number of years with high manuring to bring them back to normal.

11.4.4 Factors affecting critical levels

According to Fairhurst (1998), the following factors affect leaf nutrient concentrations and, by implication, critical levels: leaf age, leaflet rank, leaf number, palm age, fruiting cycle, planting material, palm density, fertiliser treatment, rainfall and soil properties. Only a limited number of these can be examined here, but the possibility of all these effects should be borne in mind.

11.4.4.1 Effects of different soils

In a study using 3–5 years' data from 40 field experiments conducted in Peninsular Malaysia, Foster and Tarmizi Mohamed (1988) and Foster (1995) found a number of interesting relationships of critical levels with environmental variables. On all soils the optimum leaf levels of phosphorus and potassium increased with rainfall, and the critical level of phosphorus increased with planting density. On inland soils (e.g. Rengam

series; see Section 3.5.1.1) and coastal soils the critical level of potassium declined with silt content. On coastal soil (see Section 3.5.1) the critical level of potassium also declined with soil cation exchange capacity. This series of relationships is not easy to explain in terms of physical or biological effects. 'Total leaf bases' (i.e. cations; Section 11.6.4) were strongly dependent on soil type, and were negatively correlated with the available water-holding capacity of the various soils. This relationship is almost certainly connected with the distinction between the Malaysian coastal clayey soils and the more sandy inland soils in their leaf analysis results, but is not necessarily a direct causal relationship. The prediction of yield response to single fertilisers from leaf nutrient data on 32 trials on inland soils and 20 trials on coastal soils was only moderately improved by taking into account these relationships, other than that of the total leaf bases. The marked differences in critical levels between inland and coastal soils, and volcanic and sedimentary soils elsewhere (Sections 11.6.2 and 11.6.4) have not been fully explained.

Ollagnier *et al.* (1988) also found that the critical level of potassium depended directly on the type of soil and its clay and exchange properties. These authors found that on an 'ando-like' ferrallitic soil in Indonesia not all of the potassium retained after fertilisation with potassium chloride was still in the exchangeable form. The rest was apparently held non-exchangeably on the clays, but was extractable with nitric acid. They considered that the low potassium levels in palms on this soil are due to the low K/Ca ratio: they suggest a dissolution of 'total calcium' in the soil and a large 'calcium pressure' (Section 11.4.6). The K/Ca ratio in soil solutions would then be very important in determining the very low potassium levels in the leaf, and the low critical level. This probably points in the right direction, but it is not an explanation of the effects.

The differences between the critical levels on coastal and inland soils in Malaysia are well known, with the normal ranges of nutrient to dry matter being (coastal soils and inland soils) N: 2.40–2.65 and 2.65–3.00; P: 0.155–0.175 and 0.170–0.185; and K: 0.85–1.05 and 1.00–1.15 (Foster *et al.*, 1988c; Caliman *et al.*, 1994). There are clear analogies with the effect of soil moisture found by Fallavier *et al.* (1989). The physical and biological mechanisms behind these relationships are not properly understood yet.

11.4.4.2 Effects of palm age and origin

In general, the leaf levels of nutrients and their critical levels decline with the age of the palm for nitrogen,

potassium and magnesium (Hartley, 1988, p. 510), but there is a distinct difference between the coastal soils and inland soils of Malaysia. Foster and Chang (1977) found similar declines with age in N, P, Mg and Ca on coastal soils, whereas there was no decline on inland soils. Hartley suggested that some of the inconsistency in the findings could be due to developing deficiencies with age in some of the cases, but this seems more likely on inland soils. Foster (2002) reported that the concentration in the leaflets in Indonesia declined sharply between 3 and 21 years, the changes being 2.85 to 2.40% for N, 0.173 to 0.161% for P and 0.95 to 0.74% for K. Caliman *et al.* (1994) noted that critical levels generally decreased with age in the French work, e.g. Tampubolon *et al.* (1990) found that the critical level for nitrogen declined sharply between 4 and 20 years from 2.9 to 2.5%, and to 2.4% at 28 years. The critical level for phosphorus declined also. The decline therefore appears to be a general effect. There can be genetic differences in composition, suggesting that fertiliser response will differ between genotypes (Tan and Rajaratnam, 1978). The related question of the different yield responses of different progenies was examined by Kushairi *et al.* (2001), who found a strong genotype $\times$ fertiliser interaction. However, they tested a standard fertiliser rate, half and twice the standard rate, so that the extreme rates were probably far from the economic quantities. Full and accurate yield response curves for different genotypes are needed.

Jacquemard *et al.* (2002b) investigated a related point in a number of field experiments, and concluded that in the same conditions, the composition of the leaves varied between categories (e.g. Deli $\times$ La Me), between hybrid types within the categories, and even between genotypes within the hybrid types. This suggested that the critical levels would also vary in these ways, and some preliminary information was obtained that supported this.

11.4.4.3 Effects of season and climate

The effects of the weather were reviewed by Hartley (1988, p. 511). Such effects arise mainly from seasonal differences and the soil moisture. The results were not very consistent, but he concluded that the moisture level did affect the critical level for potassium, which initially increased when the soil moisture deficit decreased, but then declined again as it tended towards zero (Fig. 11.14) (Ollagnier *et al.*, 1988). The current crop load may have an effect, and this is also correlated with the season. An excellent example of the seasonal differences is seen in the mean levels of the nutrient

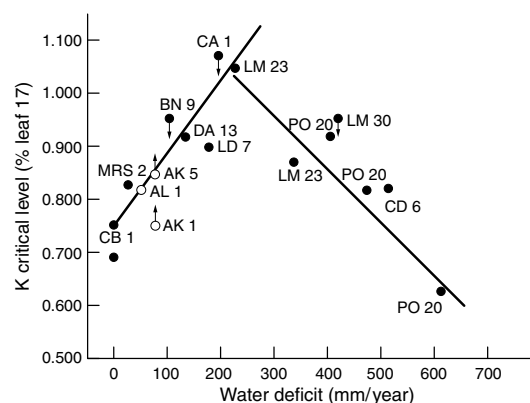


Fig. 11.14 Relationship of the critical level for potassium in the leaves with the soil water deficit by IRHO method. (After Ollagnier *et al.*, 1988.)

levels on plantations in Indonesia (Fig. 11.15). This shows a markedly larger value for N, P and K% in the latter part of the year, when soil moisture was largest.

11.4.5 Chlorine effects in the oil palm

11.4.5.1 Chlorine deficiency

This issue arose unexpectedly, because very few major effects of chlorine on field crops have been reported, and their chlorine concentration can usually vary between 0.2 and 2% dry matter with little effect. The essential concentration is at the micronutrient level, at 0.02–0.04% (Flowers, 1988; Marschner, 1995, p. 396). However, chloride is known to be essential for stomatal regulation in *Allium* species, there is now evidence that a similar effect occurs in some palms (Braconnier and d'Auzac, 1985, 1990), and it may be that a higher concentration is only needed in localised parts. This may be a mechanism for the effect of small amounts of chloride. However, a more general effect, which requires larger mean concentrations of chloride, is the osmoregulation of the vacuole and other plant parts (Flowers, 1988). This requires a much higher concentration than the upper limit of deficiency at 0.6% Cl to dry weight (or 18 mM Cl in wet tissue) (Marschner, 1995), because the concentration in the vacuole may be up to 100 mM Cl. If the osmotic effect is the important one, and the deficiency occurs below 18 mM average concentration, then the effect can only occur in a limited class of cells.

The first reports of chlorine deficiency in oil palms came from leaf analyses in Colombia (Ollagnier and Ochs, 1971a, b), when applications of potassium chloride gave

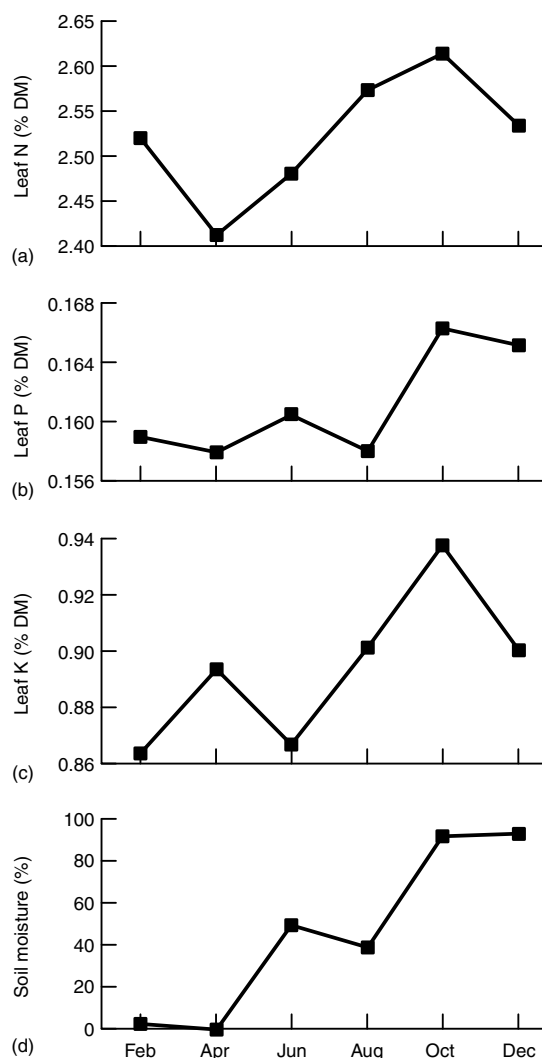


Fig. 11.15 Seasonal effects on the nitrogen, phosphorus and potassium levels in the leaves and soil moisture status measured in different seasons in North Sumatra. Soil moisture measured as available water by IRHO methods, expressed as % of AWC. (After Foster, 2002.)

an increase in yield, whilst increasing the chlorine contents of leaves from 0.18 to 0.54% dry matter, but decreasing the leaf potassium concentration. A similar effect was found in PNG (Breure and Rosenquist, 1977; Wilkie and Foster, 1990). In the latter case, potassium chloride increased chlorine levels ten-fold in leaflets and rachis, and calcium, magnesium and potassium were all increased in the rachis, but potassium was decreased in the leaflets, as in the other cases noted. The increase in

rachis potassium suggests that the element was also increased in the trunk and bunches (Teoh and Chew, 1988b). If this is correct, it means that leaflet potassium is not a reliable proxy for potassium in the rest of the palm. If it is the latter that controls bunch production, the increase in yield with KCl would thus be explained. Wilkie and Foster (1990) also showed that adding EFB, which supplied potassium but not chlorine, increased leaflet potassium, so the problem reduces to explaining why high chloride concentrations decrease potassium in the leaflets only.

Foster *et al.* (1993) made further experiments in PNG on the volcanic soils. They reported that calcium and magnesium always increased in both the leaflets and rachis when potassium chloride was supplied, with a very high increase in chlorine and potassium in the rachis, so that the increase in cations (total leaf cations or TLC) and in chlorine in the rachis were about equal (Foster *et al.*, 1993). There was little effect on the TLC in the leaflets, where the increases in magnesium and calcium were balanced by a decrease in potassium. These experiments also showed that potassium chloride gave a 10% FFB response when the high dose of nitrogen as ammonium sulfate was supplied, but only 2% without nitrogen fertiliser. On these volcanic soils the overriding deficiency was that of nitrogen, and the other effects may not show clearly in palms with nitrogen deficiency. In some cases adding chlorine to palms increased magnesium levels in the leaflets, and in one trial, in west New Britain, a yield response was attributed to decrease in magnesium deficiency. Foster *et al.* (1993) attributed the benefits of chloride to a 1–2% higher moisture percentage in the leaf and rachis tissues, although this seems small to account for the yield differences. H.L. Foster (pers. comm.) noted that leaves were turgid and green where chlorine had been given, but dull and flaccid without, which may indicate more rapid leaf cell expansion, especially in presence of extra nitrogen. The increase in water in plant tissues following application of potassium chloride is well known, for example in potatoes, but this is not necessarily associated with a yield increase in a high-potassium soil.

11.4.5.2 Causes of chlorine effects

The best hypothesis seems to be that chlorine acts as part of the anionic counterions to the cations in the vacuole and elsewhere (Tinker and Leigh, 1985), so that adding chlorine increases chloride and some cations, if other anions (mainly organic acids) are in short supply. The decreased demand for organic acids from the plant

may itself be an advantage and cause a yield response. In some tissues the ionic balance between potassium and the divalent cations magnesium and calcium seems to be altered, so that there is a lower level of potassium in the leaflets when the cation concentration in the soil solution in general is increased.

The most puzzling feature is that some of the sites reported on by Foster *et al.* (1993) were fairly close to the sea coast and should have received large amounts of wind-borne chloride originating from sea spray. Marschner (1995) pointed out that in species with the normal limit on deficiency of *c.* 1 mg Cl/g leaf dry weight (*c.* 3 mM in wet tissue), the whole plant requirement would be supplied by a very few kg/ha chloride. This is supplied from rain in areas a long way from the sea, whereas the chlorine input near the sea is usually at least ten times this, depending on wind and rainfall. Possibly the very heavy rainfall tended to dilute and wash out the chlorine.

There are four outstanding questions in this problem. First, why is there a shortage of chloride at all, with a very heavy rainfall close to the sea? Secondly, what are the unusual properties of the volcanic soil that causes the problem to occur? Thirdly, why does the leaflet content of potassium decrease when that of the rachis increases as potassium chloride is added? Fourthly, what is the mechanism whereby a yield response to chlorine is produced? Foster (1995) showed data for four major soil types (Table 3.20). Three have pH values between 4 and 5, whereas PNG volcanic soils are pH 6.10. The PNG soil contains 8.10 meq. 100 g Ca, four times more than any other, and has a K/total exchangeable cations ratio of 0.024, the others being 0.20, 0.24 and 0.20. This soil is certainly very different from the norm of Asian oil palm soils, but it is not obvious why that should have such effects on chlorine nutrition. Differences in leaf composition were less striking. It seems that more detailed work than field experiments and routine tissue analysis are needed to elucidate this problem.

The effect of chloride and sulfate as anions in fertilisers was investigated by Lim K.C. *et al.* (1995) on a Rengam inland soil. No effects were found on the FFB yields, and little effect on leaf composition. They concluded that the palms had ample amounts of chlorine from being close to the sea coast, and that chlorine deficiency appears to be a specialised and regionalised phenomenon.

11.4.6 Cation antagonism

The importance of ratios between one of the leaf cations and the TLC (Section 11.6.4.5) suggests there is a generalised antagonism between the main nutrient cations, which also appears in various ways in different soil and

plant processes. This is not surprising if there is a limited number of cation-exchange sites, and there is a competitive equilibrium between the cations for these. These cations are mainly potassium, magnesium and calcium although sodium may be involved if it is present in significant amounts. The competition possibly appears in uptake from external media because of competition for some root uptake sites, and may also appear in the generalised effect on the electrical potential difference across the plasmalemma, which affects the rate of cation uptake (Marschner, 1995, p. 39).

Competition occurs within the soil, as there is usually a limited quantity of anions in the soil solution and cation-exchange sites on the solid surfaces, and these are partnered by cations in relative amounts that are determined by the exchange equilibria of the soil exchange complex. The net effect is that adding one of these cations as a salt may reduce the relative concentration of the others in the solution, as happens with the activity ratio $K/(Ca + Mg)^{1/2}$ (Beckett, 1964). To this must be added the purely physiological effects, such as the Mg-K and Mg-NH₄ uptake antagonisms.

11.5 SOIL COMPOSITION AND PLANT NUTRITION

11.5.1 Soil analysis and its uses

Soil analysis can only give a rough indication of the likelihood of a nutrient deficiency in plants, and one would not look to this technique in the first instance to decide on fertiliser rates in an existing plantation. The subject is plagued by terms that are widely used, but are in reality very complex and difficult to define. For example, 'available' nutrient does not necessarily mean 'in solution'. Most nutrients (except for nitrate and chloride) are also held by adsorption on the soil solids, and the concentration in the soil solution is controlled by this equilibrium. As the nutrient is absorbed by a root, more desorbs from the soil, but the loss of the sorbed material decreases the equilibrium level in the soil solution. Nutrients have to be transported to the root surface before uptake, by mass flow (convection) or by diffusion (Tinker and Nye, 2000). The rates of diffusion vary widely, so the limit on uptake may lie in the desorption step, the diffusion/convection step or the actual uptake step. This complex process has to be condensed by soil analysis into a single value, and it is hardly surprising that it often fails.

One therefore looks for large differences or extreme values in soil analysis, where there is a greater probability that any conclusion is correct. Extremely low values for particular elements might be taken as an indication of a

deficiency, or as confirmatory evidence of deficiency following leaf symptoms or leaf analysis, but the function of soil analysis for perennials is more in relation to the selection of correct rates of nutrient addition (Section 11.6). It is of greater use in annual crops than with treecrops, because of the need to follow the soil changes resulting from differing crops and treatments year to year.

In a few cases it has been shown that there is a defined level of a nutrient in the soil that is sufficient for palms. One of these appears to be the soil exchangeable Mg/K ratio, which must be above 2 to avoid magnesium deficiency on acid sands soil in West Africa (Tinker and Ziboh, 1959b; Tinker and Smilde, 1963a). A similar Mg/K ratio was also found to be important on a variety of soils by Dubos *et al.* (1999), although it does not fit some Malaysian soils, where the Rengam soil has a very low Mg/K ratio, but only occasional deficiency. Potassium deficiency has been related to the fraction of the exchange complex occupied by potassium (Tinker and Ziboh, 1959b; Foster *et al.*, 1985a; Hartley, 1988, p. 517). It seems anomalous that this should be found, when the exchange capacity value is that determined in pH 7 ammonium acetate, whereas the soil pH is normally 2–3 pH units more acid. Tinker (1961) found that the exchangeable cation ratio $K/(Ca + Mg + 2.5 Al)$ was equally predictive in acid solution. Subsequently, Tinker (1964a, b) showed that the extended activity ratio equation $K\sqrt{Ca + Mg + P^3A}$ was also a good guide to potassium status on acid sands soils of West Africa. All of these parameters are different ways of expressing the balance between potassium and the other exchangeable ions on the soil. Davila *et al.* (1998) studied the potassium dynamics of the oil palm soils in the eastern part of Colombia, which show a considerable ability to release slowly exchangeable potassium, probably from vermiculite. The same authors have studied soil sulfur (Davila *et al.*, 2000a) and micronutrients (2002b) by in soil and palm leaf tissue, and suggested that sulfur is deficient in these soils. The relationships between micronutrients in soil and palms were variable and uncertain.

Sometimes simple analyses are useful, e.g. the data of Foster and Chang (1977) have been used in Table 11.12 (Goh *et al.*, 1994). Several other soil measurements form part of the Foster (2002) system (Section 11.6.4), for example that analyses of soil for phosphorus would be useful in indicating deficiencies, but again there are problems in deciding the effects of prior fertiliser addition. Foster (2002) *et al.* (1988a) found that on inland Malaysian soils the Bray 2 analysis procedure for extractable phosphorus corresponded with both leaf phosphorus values and yields (Table 11.13) (Foster *et al.*, 1988a). In the small number of coastal soil sites no relationship was found.

Table 11.12 General guidelines to estimate potassium responses from soil exchangeable potassium

Location	Soil exchangeable K (cmol/kg)	Response
Coastal	>0.25	Nil
	0.15–0.25	Marginal
	<0.15	Good
Inland	<0.20	Good

After Goh *et al.* (1994a).

Table 11.13 Mean soil and leaf P levels in Po control treatments with FFB yields, in 10 Malaysian experiments

Trial no.	Soil extr. P (ppm) ^a	Leaf % P	FFB yield (t/ha per year)
Inland soils			
8	5	0.133	14.02
41	39	0.152	27.92
43	12	0.153	20.18
44	163	0.168	26.63
45	144	0.165	25.44
46	126	0.171	18.72
Coastal soils			
4	22	0.155	22.15
5	47	0.156	30.72
6	41	0.159	26.42
10	59	0.155	24.45

^aBray II.

After Foster *et al.* (1988a).

However, soil analysis has very little part to play in existing plantations that have been using placement of fertiliser in a weeded ring around the palm trunk, which is the standard method in most plantations. Often this is done very irregularly, so that parts of this fertilised ring receive an enormous loading in nutrient per hectare. Kee *et al.* (1995c) reported that the soil under the fertilised ring was much more acidic than the rest (Table 11.14), and had a four-fold increase in exchangeable potassium at 60 cm depth. The fertility of the rest of the surface soil must thus be far lower than would be indicated by the palms' yields and leaf analyses (Section 11.9.3). Tinker (1959) suggested that under mature palms, and with a soil that was naturally poor in nutrients, the constant 'inner cycle' return (Fig. 11.1) of nutrients would tend to make the soil level more uniform, and over time soil and leaf tissues would come into a rough equilibrium. Now that broadcasting is becoming more popular because it can be mechanised,

Table 11.14 Effects of nitrogen/potassium fertiliser addition on soil pH after 7 years, and 5 months after a single split addition^a

Fertiliser treatment	Depth (cm)	Palm circles		Interrows		Frond piles	
		0 ^b	5 ^b	0	5	0	5
N ₀ K ₀	0–15	4.23	4.41	4.51	4.53	4.49	4.58
	15–30	4.12	4.24	4.47	4.41	4.37	4.38
	30–45	4.22	4.18	4.47	4.40	4.33	4.29
	45–60	4.24	4.22	4.37	4.39	4.31	4.25
	60–90	4.03 ^c	4.13 ^d	4.18 ^c	4.36 ^d	4.22 ^c	4.21 ^d
	90–120	4.01 ^c	4.09 ^d	4.18 ^c	4.39 ^d	4.22 ^c	4.15 ^d
N ₁ K ₁	0–15	3.84	3.59	4.37	4.57	4.48	4.55
	15–30	3.90	3.66	4.24	4.42	4.40	4.40
	30–45	3.88	3.74	4.16	4.28	4.32	4.25
	45–60	3.87	3.78	4.13	4.22	4.28	4.31
	60–90 ^d	nd	3.92	nd	4.17	nd	4.31
	90–120 ^d	nd	3.97	nd	4.36	nd	4.37
N ₂ K ₂	0–15	3.76	3.35	4.14	4.38	4.34	4.26
	15–30	3.70	3.48	4.00	4.18	4.28	4.43
	30–45	3.70	3.54	3.90	4.05	4.21	4.21
	45–60	3.66	3.58	3.93	4.02	4.18	4.15
	60–90 ^d	nd	3.64	nd	4.17	nd	4.14
	90–120 ^d	nd	3.65	nd	4.21	nd	4.10

^aN₁K₁ at 0.375 kg N + 0.875 kg K/palm; N₂K₂ at 0.75 kg N + 1.75 kg K/palm.^bMonths after treatment. 0 is just before, and 5 is 5 months after fertilising, all in the palm circle.^cOne replicate only.^dTwo replicates only.

nd: not determined.

SE: 0–15 cm = 0.08; 15–30 cm = 0.06; 30–45 cm = 0.06; 45–60 cm = 0.06.

After Kee *et al.* (1995c).

it is possible that soil analysis will prove to be more useful than in the past (Bosshart *et al.*, 1990).

11.5.2 Identification of likely deficiencies

Soil investigations are of great value in examining proposed sites for plantations (see Sections 3.4.2 and 8.1.3). The most important issues in site selection are soil physical properties, especially those affecting water relationships or erosion. However, the cost of fertiliser is a large part of the total costs of running a plantation (Section 11.3.2.3), and indications of the need for particularly large or small amounts of fertiliser are useful. Thus, a large supply of slowly exchangeable potassium that provides long-term sufficiency of this element, as in the coastal Bria series soils of Malaysia, is a major advantage. Similarly, any very sandy soils will require high levels of potassium and magnesium fertilisers, and ando soils and volcanic allophanic soils may need much phosphate. Broad generalisations such as this, based on sampling large unfertilised areas, should focus attention on unusual features.

11.5.3 Calculation of fertiliser applications

Soil analysis for perennial crops has only an indirect relationship to growth demand (Section 11.1.3.1), because the objective is to bring a soil to a non-deficient level for the relevant nutrients, and then maintain it there from year to year by fertiliser additions. This is very different to traditional soil analysis for annual crops, where the soil composition has to be prepared for a short spurt of growth and nutrient uptake by a particular crop. If leaf analysis has indicated a deficiency in palms, soil nutrient levels must be gradually increased until the leaf analysis and soil analysis values remain stable, with the leaf analysis at a sufficient level. If the soil levels are kept at too high a level, this can cause unnecessary losses due to excessive surface runoff and leaching, and to sorption processes that remove the nutrient from equilibrium with the soil. This applies particularly to phosphorus because it is so readily sorbed, possibly to potassium and magnesium where certain illitic clay types are present, and to nitrogen if the applications

encourage the unnecessary build-up of organic matter. It is sensible to follow the soil composition by regular soil analysis, to determine whether increased fertiliser rates really are raising the soil level, and to determine the minimum sufficient level and the annual input that will maintain this in the future.

11.6 PRACTICAL SYSTEMS FOR FERTILISER TYPE AND RATE ASSESSMENT

11.6.1 Nutrient balance approach

11.6.1.1 Nutrient balances

The simplest system is based on nutrient balance. The nutrient balance (Cooke, 1967; Ng, 1977) is the foundation of modern plant nutrition in the field, and has recently been advanced for dealing with soil nutrient depletion in African agriculture in general (Smaling *et al.*, 2002). It is also a dynamic approach, as against the essentially static classical view. A nutrient balance (Fig. 11.16) (Henson, 1999c) has been drawn for potassium,

as particularly detailed data for this simple element are available (Teoh and Chew, 1988b; Henson, 1999c). Magnesium and calcium also have relatively simple chemistries. The other elements may need more care in developing nutrient balances, because of buffer stores or alternative sources of nutrient. This applies to phosphate because of its sorption/desorption behaviour, nitrogen because of its microbial reactions in the soils, and metallic trace elements because of their complex valency change, precipitation or sorption reactions (Tinker, 1986).

The palm data are from fertilised palms on Selangor soil, with yield of 32 t/ha/yr, and 148 palms/ha (Teoh and Chew, 1988b). The data have been used by Henson (1999c) to construct a potassium budget of the palm ecosystem. The shoot increment (Fig. 11.16) is calculated from the potassium content of the trunk and frond bases, which accumulated there during 12.5 years (ignoring the first 3 years). These data include a considerable amount of potassium in the leaf bases, and must be adjusted as the leaf bases are shed.

In practical agriculture the amount of potassium recycled in POME and EFB is important. This has

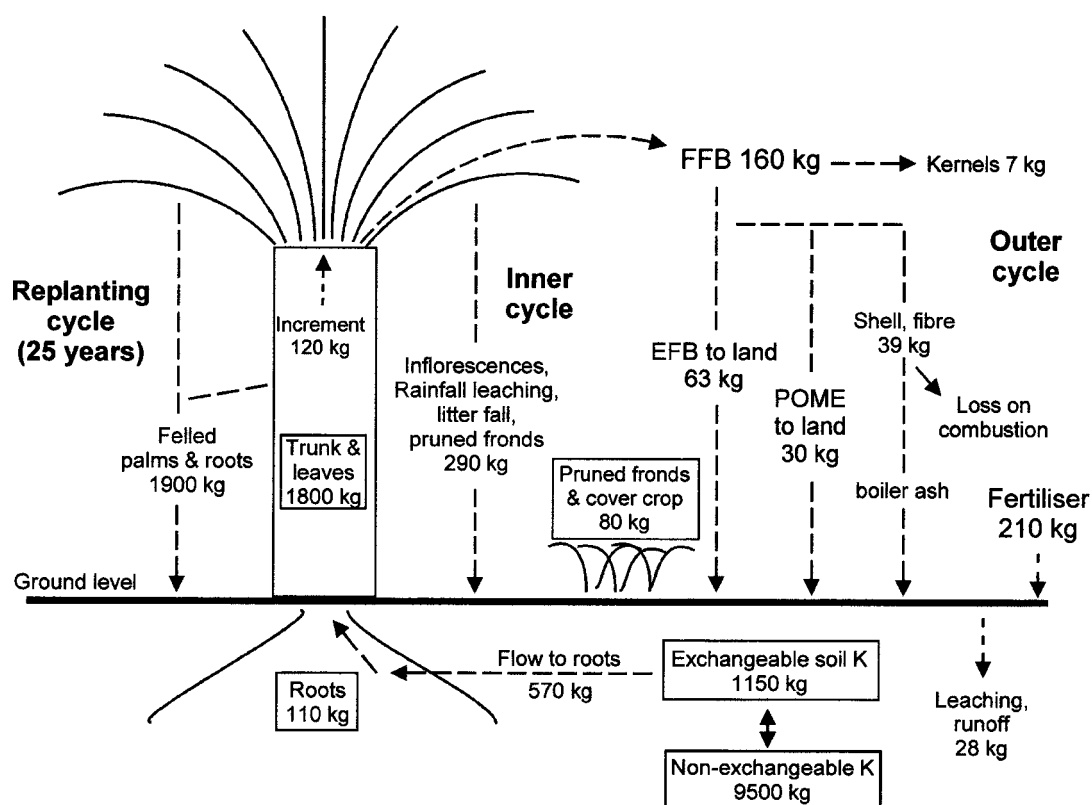


Fig. 11.16 Total demands and sinks for potassium in an oil palm field with 30 ton FFB yield. (Amended from Henson, 1999c.)

been calculated from the mean amounts of potassium in EFB or in POME, per ton of FFB (Gurmit *et al.*, 1999b; Ma 1999b), which have been applied to the yield of FFB from the manured Selangor soil palms. Because this soil is so rich in potassium, the FFB contains the high concentration of 4.95 kg K/t FFB, compared to 4.32 kg/t for fertilised palms on inland soils, and only 3.37 kg/t for unfertilised palms on the same soils. Such differences need to be taken into account in accurate fertiliser demand calculations. The actual amounts in accurate the EFB and POME may therefore have been underestimated. The value of 39 kg for potassium in the ash from shell and fibre has been calculated from the weight of fibre produced from a 20-ton field (Chan 1999) and the percentage of potassium in fibre from a typical mill (1.44%, Goh K.J., pers. comm.). These values are in very good agreement with those used by Vis *et al.* (2001). The results will depend upon the potassium status of the palms, and a full potassium balance including all terms needs to be made for a single field.

If the fertiliser rate of 210 kg K/ha is used, and the recycling is successful, this shows a small excess of application, that is certainly wasted in part on the Selangor soils. Without recycling there is a deficit of around 80 kg K/ha/yr. This amount could probably be supplied by a Selangor soil for many years, though little work has been done on its long-term dynamics. Such a deficit would be serious for a low-fertility inland soil.

11.6.1.2 Growth demand

The growth demand due to the increasing growth of the palm includes part of the nutrients in the FFB production. The losses resulting from the removal of oil and kernels can be measured fairly easily (Section 11.1.4). After calculating the nutrient offtake in FFB, the amount returned to each field in bunch ash, EFB and POME can be either deducted from the FFB loss or added to the 'fertiliser' contribution in Fig. 11.1. It is a reasonable assumption that all potassium will be water soluble, and all nitrogen and phosphorus compounds will be soluble or biodegradable, except for bunch ash. It is more difficult to determine the environmental losses in surface runoff, erosion and leaching in drainage water (Section 11.7.4.1) and volatilisation (Sections 11.7.4.1 and 11.9.2.2). If the palms are young the nutrient relations of the cover crop need to be included in the calculations (see Section 8.4.2). The uptake efficiency (Section 11.6.1.4) can be calculated as:

$$\text{Uptake efficiency} = \frac{100\% (\text{Fertiliser applied} - \text{Actual losses in kernels, factory wastes} - \text{Environmental demands})}{\text{Fertiliser applied}} \quad (11.5)$$

A set of typical balance data for all major nutrients is given in Table 11.15 (Ng *et al.*, 1999). These are drawn from a number of different publications, so they do not

Table 11.15 Oil palm nutrient balance assuming return of EFB and POME, but no change in soil potassium, and calculation of fertiliser needed to support yields of 20 and 30 t FFB/ha

Nutrients (kg/ha per year):	20 t/ha yield				30 t/ha yield			
	N	P	K	Mg	N	P	K	Mg
<i>Demand: stored/lost</i>								
Stored in trunk per year	42.4	4.1	121.6	10.2	42.4	4.1	121.6	10.2
Shell	3.0	0.1	1.4	0.2	4.5	0.1	2.1	0.3
Fibre	5.2	1.3	21.5	1.9	7.8	1.9	32.3	2.9
FFB (without shell + fibre)	57.8	9.0	63.5	20.1	86.8	13.5	95.2	30.1
Runoff: lost	15.2	1.0	21.6	2.1	15.2	1.0	21.6	2.1
Leaching: lost	3.4	0.9	6.3	3.4	3.4	0.9	6.3	3.4
Eroded sediments: lost	2.4	0.0	0.0	0.2	2.4	0.0	0.0	0.2
Total 1	129.4	16.4	236.0	38.0	162.5	21.6	279.1	49.2
<i>Supply</i>								
EFB	11.5	1.42	41.7	1.8	17.2	2.13	62.6	2.8
POME	4.4	0.91	20.7	3.9	6.6	1.37	31.1	5.8
Rainfall (nutrients from rain)	17.0	2.40	31.6	4.8	17.0	2.40	31.6	4.8
Total 2	32.9	4.73	94.0	10.5	40.8	5.89	125.3	13.4
Nutrient input needed = Total 1 – Total 2	96.6	11.66	142.0	27.5	121.7	15.70	154.0	35.8

Data from various authors (see original publications).
After Ng *et al.* (1999).

represent any specific field, but they give the magnitudes involved in the balance. Usually, adequate local data can be found, but for some processes there are no really good data.

As stated above, the slow soil processes of dissolution and desorption for nutrients are the most difficult to determine and quantify. Sorption of phosphates may remove soluble phosphate ions entering the soil solution (Sample *et al.*, 1980). The phosphate in Christmas Island Rock Phosphate (CIRP) is normally treated as being available, but this is dependent upon soil pH and the actual type of CIRP, and dissolution can be quite slow at moderately acid pH. However, Foong and Syed Sofi (1995) found that annual and biannual applications of CIRP were better than 4-yearly application, suggesting that dissolution was fairly rapid. Some soils can supply potassium or phosphate slowly over a long period, and it may be possible to continue cropping in a sustainable way (Chan, 2000a) without generating a nutrient deficiency, but without supplying the whole nutrient balance amount by fertilisers. Fallavier *et al.* (1989) studied the release rate of potassium to water in soil columns in the laboratory, but this is not relevant. Fallavier and Olivin (1988) showed longer term release in volcanic Indonesian (Aek Loba) soils. In general, a significant content of 2:1 clays, especially those with potassium-containing interlayers, or a large content of potassium minerals that dissolve at a moderate rate in acid solvents (Foster, 2002) or give up potassium progressively to cation-exchange resin, is a good indication that potassium reserves may be extractable by cropping. This can occur simply by the reduction of the soil exchangeable potassium due to cropping, without replacing the offtake by fertiliser addition. The potassium potential is thus reduced, but it must remain large enough for maximum yield to continue to be obtained. The assumption that because non-exchangeable nutrients can be extracted by plants they can be exploited whilst still maintaining high yield is not necessarily correct. More research on the maximum amount that can be extracted from the coastal soils would be advisable, using long-term fertiliser experiments and release to cation-exchange resins.

It is convenient to group a number of other processes in which nutrients are gained from or lost to the environment as environmental demands. The gains can be wet or dry deposition from the atmosphere, or surface wash and erosion products carried in from further up the slope. The losses are volatilisation of ammonia or denitrification products, erosion of topsoil, surface wash of applied fertiliser and leaching. Most of these vary with environmental conditions, and may be difficult

either to measure or to predict. It seems possible that these may be relatively small on high-yielding fields, so great accuracy may not be needed. They are discussed in detail in Section 11.7.4.

11.6.1.3 Deficiency demand

Simple nutrient balances as in Table 11.15 are not adequate to guide fertilisation if there is an existing deficiency demand, because this requires an investment of nutrients in both palm tissues and soils (Section 11.1.3.2). If the palm is deficient according to leaf analysis (Sections 11.4.3 and 11.6.2.3), the quantity needed for the palm may be estimated from the difference between the present nutrient concentration, and the absolute critical level, using published data for potassium (Teoh and Chew, 1988b) (Section 11.4.2.2). The data for other elements is still inadequate. However, meeting a deficiency demand also means increasing the status of the nutrient in the soil, and there is no precise information on how large this increase must be to support the maximum yield on different soil types. This is particularly problematic for phosphate because of the strong adsorption on soil clays and oxides (White, 1997). At present there are few soil analysis criteria for nutrient sufficiency for phosphorus, potassium and magnesium in oil palms, for reasons discussed above (Section 11.5.3), and such criteria will rarely be reliable for nitrogen for any crop (Barber, 1995). The relationship between leaf concentration and a soil analysis parameter, if it is validated in fertiliser experiments on the same soil type, could predict the desirable soil concentration to eliminate the deficiency. However, this is only applicable where fertilisers are broadcast. If fertilisers have recently been applied by placement, then it is only possible to progress by trial and error.

In this case rates of fertiliser that are somewhat larger than the nutrient balance requires should be supplied, and then both the soil and the leaf composition monitored until the leaf analyses reach the required levels, as indicated above (Section 11.5.3). After this, the steady-state nutrient balance quantities should be supplied. During this period the uptake efficiency (Equation 11.6) will appear to be less than as given in Equation 11.5.

$$\begin{aligned} \text{Uptake efficiency} = & \\ & 100\% (\text{Fertiliser applied} - \text{Actual losses in} \\ & \text{ kernels, mill wastes} - \text{Environmental} \\ & \text{ demands} - \text{Nutrients placed permanently in} \\ & \text{ the soil and in the existing structure of the} \\ & \text{ palm}) / \text{Fertiliser applied} \end{aligned} \quad (11.6)$$

11.6.1.4 Fertiliser efficiency in a palm plantation

The nutrient balance is the most fundamental way of expressing the nutrient flows in a field, and the usefulness of applied fertiliser. However, an alternative method, using similar data, is to define a 'fertiliser efficiency' in one of several ways, that may be obtained from a nutrient balance or a fertiliser experiment (Teoh and Chew, 1988b).

The first way assumes that the nutrient balance is complete, and that all flows are known and accounted for. Then

$$\text{Fertiliser uptake efficiency} = \frac{100 \times (\text{Fertiliser applied} - \text{losses in kernels and factory wastes} - \text{losses in environmental demands})}{\text{Fertilisers applied}} \quad (11.7)$$

Any unknown waste of fertiliser will of course give an efficiency that is too large. Sometimes it may be uncertain whether a process is a loss or not. Thus during the correcting of a deficiency (Section 11.6.1.3) the soil nutrient concentration must also rise. If this unavoidable transfer of nutrient is considered to be a waste, efficiency will be as in Equation 11.6. Any nutrients that enter the soil irreversibly are of course also losses.

The alternative approach to this is to make a simple comparison between plots receiving and not receiving the fertiliser, and so avoid having to measure all the nutrient flows. If this is done, it is necessary to define the conditions carefully to determine exactly what is being measured. If the plots have been receiving the fertiliser and no-fertiliser treatments for a long time, they will both be in equilibrium. There is then no loss of nutrients placed in the soil because of deficiency demand during the experimental period. However, if the measurement period is soon after the treatments were initiated, the plots receiving fertiliser will become enriched in that nutrient because of deficiency demand, as noted above. In the first case the equation defining the fertiliser efficiency is

$$\text{Fertiliser uptake efficiency} = \frac{100 \times [(\text{Nutrient gained by manured palm} + \text{that removed in FFB}) - (\text{Nutrient gained by unmanured palm} + \text{that removed in FFB})]}{\text{Nutrient in fertiliser}} \quad (11.8)$$

In the second case, changes in the nutrients in the soil of the two types of plots would be allowed for as follows:

$$\text{Fertiliser total efficiency} = \frac{100 \times [(\text{Nutrient gained by manured palm} + \text{that in FFB} + \text{gained by the soil}) - (\text{Nutrient gained by unmanured palms} + \text{that in FFB} - \text{that lost from the unmanured soil})]}{\text{Nutrient in fertiliser}} \quad (11.9)$$

$$\text{The last term allows for the possibility that nutrient is being depleted from the unmanured soil.}$$

Sometimes it is considered that only nutrient taken up by the actual bunches has been utilised, though this seems a rather simplistic view. If so,

$$\text{Nutrient yield efficiency} = \frac{100 \times [(\text{nutrient removed in fertilised FFB}) - (\text{nutrient removed in unfertilised FFB})]}{\text{Total fertiliser applied}} \quad (11.10)$$

Recycling of POME and EFB does not undermine these calculations, but the nutrient in these sources must be included with that in the fertiliser, or it must be deducted from the nutrient being removed in FFB.

The method of calculation given for the soil contribution of K in fertilised plots (Teoh and Chew, 1988b) is:

$$\text{K from soil on fertilised plots} = \frac{(\text{Total K immobilised in plant and in FFB on fertilised plot}) - (\text{Fertiliser K applied} \times \text{Fertiliser uptake efficiency \%})}{\text{Fertiliser uptake efficiency \%}} \quad (11.11)$$

When the uptake efficiency as defined above (Equation 11.6) is substituted into the equation, the latter reduces to the potassium used in the growth and yield of the unfertilised palms. This implies that the same amount of nutrient is supplied by the soil when it is fertilised, which is not necessarily true; the same applies to Equation 11.7. These measures can give useful insights, but their real meaning needs to be considered carefully.

A more general method for a multirate fertiliser experiment is shown in Fig. 11.17 (AAR, 1999). In this, the applied nutrient per year is plotted against the gross nutrient requirement per year, as derived from a nutrient balance study (i.e. the nutrient taken up by FFB, increasing the general nutrient level throughout the palms, and stored in the newly formed parts of the palms). The slope of this graph is then the uptake efficiency, as defined in Equation 11.7, for each increment of an increasing application rate. The fertiliser efficiency is therefore a variable quantity dependent on the application rate, and tending towards zero at very high rates, where no additional consumption occurs, but the environmental losses increase without limit. It cannot be defined for each soil series as a constant soil parameter.

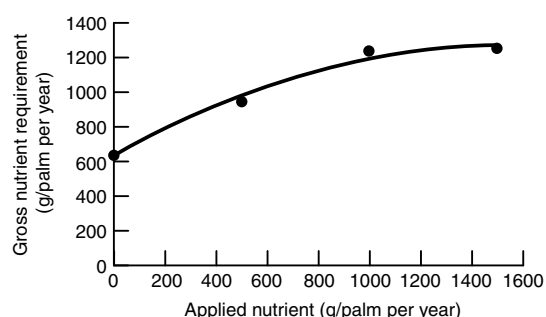


Fig. 11.17 Effect of the rate of nitrogen fertiliser on gross uptake rate of nitrogen by palms. The slope of the curve is the uptake efficiency, which varies with rate of fertiliser applied. (After AAR, 1999.)

Teoh and Chew (1988b) used this approach to determine that the fertiliser potassium uptake efficiency was largest on the Munchong soil series, at 83%, and lowest on the Briah series, at 19%, with other tested soils lying between 42 and 54%. The low Briah value almost certainly arises because the fertiliser is only supporting the supply of slowly available soil potassium, which is quite large on this series, and the presence of fertiliser potassium may slow down this release. In a situation like this, where a low efficiency is due to release of soil potassium rather than to large losses from the field, the fertiliser rate must be reduced to see whether more of the soil potassium can be used. It is essential to understand the processes that underlie an efficiency value.

The soil properties that determine fertiliser uptake efficiency, as defined above, appear to be bulk density, effective soil volume, organic carbon, pH and rainfall, and also whether or not the area is terraced (Chew, P.S. pers. comm.). All of these have clear links to the processes that cause nutrient loss. At present, nutrient uptake efficiency is a concept that is difficult to discuss because it is often dealt with as a 'black box' process, where the real processes of loss are hidden.

Chan *et al.* (1993) studied efficiency of fertilisers in a large multi-factorial experiment, but this used the term 'efficiency' in a rather different way to that employed here. Another approach was put forward by Fairhurst (1999). This requires measurement of the nutrient uptake by appropriate measurements on palm and FFB, as in INFERS (11.6.2). The data are then used to derive a series of efficiencies – agronomic, physiological and recovery. These efficiency values are interesting, but it is not clear whether these data are useful guides to estates. A later paper (Prabowo *et al.*, 2002b) reverted to the calculation method of Teoh and Chew (1988b) as

given in Equation 11.6, in which the differences in uptake by fertilised and unfertilised palms are compared with the applied fertiliser. Field experiments in Sumatra, on rhyolite, sandstone and 'claystone' soils showed that the % efficiency was always larger with a small application (e.g. K_0-K_1) than with a larger application (K_2-K_1 or K_2-K_0). This follows directly from the curvilinear response of yield to nutrient supply (Figs 11.11, 11.17), and is to be expected. The curvilinear graphs relating some nutrient adsorption to the soil solution concentration will tend in the same direction. They also found that the % efficiency determined usually decreased in the order $K > N > Mg > P$. This also is expected. Potassium is only weakly adsorbed on the soils colloids, so a large fraction remains in solution, and the sorbed K rapidly desorbs if the K concentration in the soil solution declines. In principle N is capable of giving a high efficiency, if it is wholly in a soluble form. However, urea is partially lost by volatilization, the soluble N enters the soil nitrogen cycle and becomes bound, and remaining soluble N is easily lost by leaching. A combination of these effects gives a moderate efficiency percentage. Magnesium is moderately strongly adsorbed on both clay and organic surfaces in the soil, and plants do not have a high uptake rate for this element (Tinker and Nye, 2000). Phosphate is relatively strongly adsorbed on nearly all soils except peats, and its efficiency will almost always be low; this is not an effect confined to Sumatran volcanic soils, as suggested by Prabowo *et al.* (2002b).

This raises another problem in the meaning of efficiency, which is the retention and subsequent use of a nutrient in a following year. For example, many UK cereal soils have been so well fertilised with P in the past that they do not need a further application in any one year. The amount applied is then usually the amount removed in the crop, thus maintaining the nutrient balance. In such cases the efficiency of the P is close to 100%, in the absence of leaching or erosion. For a perennial crop like palms such multi-year balances need consideration.

The difficulty is that these efficiency values are not fundamental, but depend upon the nutrient state of the palm and the soil, and the rate applied. As Prabowo *et al.* (2002b) point out, the application of another element, for example N, often alters the efficiency of P and K. This could be a short-term physiological effect, because nitrate usually enhances K uptake. More likely it is due to the increased yield of FFB and growth caused by the N, so that growth demand is increased, and the efficiency increased through this. A demand analysis is therefore needed to understand the mechanism.

What is the practical application of efficiency values? The profitability values (Fig. 11.12) are those most needed in a commercial plantation. If a given rate of fertiliser produces a profitable yield response, the estate will apply fertilisers to the point of maximum profit – if it can determine this. The efficiency value gives no direct help in determining this point. The efficiency is more helpful as a guide to where losses might be occurring, but they are not a definite indicator. A low efficiency may be caused by a necessary short-term build-up of nutrients in the soil, in which case there is not a problem. Alternatively they might be building up in the soils simply because the fertiliser rates are excessive, in which case the rates should be reassessed by methods given here. Or it could be due to large losses by leaching or other mechanisms (11.7.4), in which case a detailed field study is necessary to correct this.

11.6.1.5 Nutrient uptake modelling

The nutrient balance is a simple type of model, with a normal time step of 1 year. Other models are discussed later, but they are almost entirely statistical models, based on correlations between various quantities. There are now also various mechanistic whole-plant, whole-crop and forest uptake models, which aim to model the uptake step as part of larger models (Tinker and Nye, 2000). For example, Eckersten (1994) modelled the growth of coppiced willow trees. Much simpler models of nitrogen cycling and leaching are also used by fertiliser companies as part of their sales back-up. These subjects have been omitted deliberately from this book, because they are still very much in the development phase, and there seems little prospect of applying them practically in the near future to oil palms. Existing oil palm models are still almost entirely above ground, and information about the soil–root system is still too incomplete. This area is certainly a promising research subject for the future, but the greatest present need of the oil palm industry is for more precision at the practical level.

11.6.2 INFERS system

11.6.2.1 Structure of INFERS

The Applied Agricultural Research group in Malaysia has developed a linked group of models for oil palm management over several years, called AA AeGIS (Kok *et al.*, 2000). This includes a model for site potential yields (ASYP) (see Section 10.7.3) (Kee *et al.*, 1994), a model for predicting the fertiliser requirement, Integrated Site Specific Fertiliser Recommendation System (INFERS), and expert systems for determining the

best month for fertiliser application, and the timing and allocation of different fertilisers. Only the parts referring specially to fertilisers (Kee *et al.*, 1994) will be discussed here, because ASYP is more appropriately dealt with in Chapter 10, as part of general plantation management. The system includes the use of Global Positioning Systems (GPS) and Geographical Information Systems (GIS), to allow precise reference to position in the plantation, and the display of combined or compound spatial information in the same reference frame.

11.6.2.2 The nutrient balance

A large part of INFERS depends on the nutrient balance, and has been developed on from Fig. 11.18 (Kee *et al.*, 1994). A main input to INFERS is the targeted site potential yield from ASYP. If INFERS is applied in estate management, the nutrient balance should be done, not on the actual historical yield, but on the projected SYP in this field. The immediate aim is to maximise the yield, and the correct amount of fertiliser may need to be added at once. This allows the nutrient in the FFB to be calculated at the higher yield level, but the consequences for the composition of the palm must be estimated. Other systems appear to work more on a historical basis, and therefore approach the desired steady-state high yield condition more gradually.

The practical application of the nutrient balance demands accurate data. The amounts of elements that are immobilised in the palm or transferred out with the FFB appear to be fairly constant with properly fertilised palms, but very different when comparing fertilised and deficient palms, or palms on very different soil types. The removal of potassium in FFB was 4.32 g K/kg FFB for manured palms on inland soils, 3.37 g/kg for unmanured palms on inland soils, and 4.95 g/kg for both manured and unmanured palms on coastal soils (Teoh and Chew, 1988b). Thus, very different amounts of potassium may be removed in the same quantity of FFB, and this probably carries over into the composition of POME and EFB, although no data have been seen by us. The total potassium content in palms will also be greatly altered by its availability. Unmanured palms on inland soils contained 3–4 kg K/palm, and manured ones 8–12 kg K/palm, whereas unmanured palms on coastal soils contained about 9.5 kg K/palm, and manured ones 13–14 kg K/palm (Tables 11.5 and 11.16) (Section 11.4.2.1). It is therefore dangerous to assume a single constant composition for palm parts in computing a nutrient balance. However, there is a reasonable correlation between the amounts of nutrient in various plant parts, in that fertilising increases the size of all plant organs and their

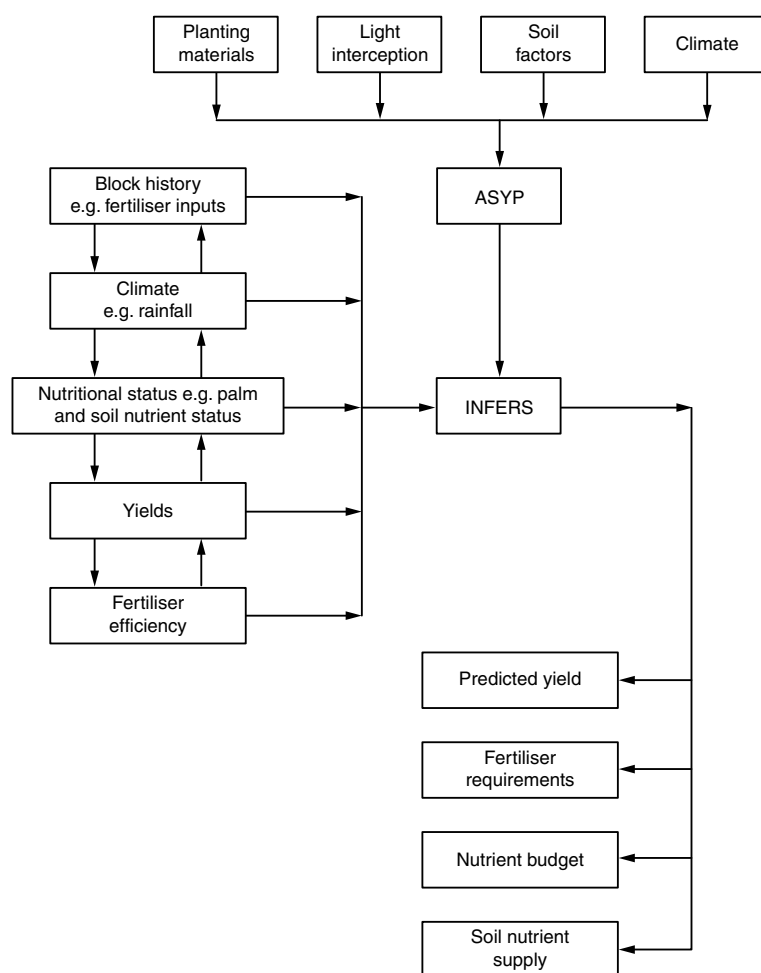


Fig. 11.18 Inputs and outputs for the INFERS fertiliser prediction system. (After Kee *et al.*, 1994.)

nutrient content (Goh, K.J. pers. comm.). It should therefore be possible to calculate the amount of potassium in different plant parts if the amount in the leaflets is known, and so start to compute the deficiency demand, on most soil situations (Section 11.4.6).

An assessment can then be made of the total new supply needed for the growth demand in fertilisers. Ng *et al.* (1999) gave an example for Munchong series soil, with a nutrient balance for potassium, phosphorus and magnesium assuming either a 20 t or 30 t FFB yield (Table 11.15). They estimated that returning POME and EFB would return about 73% of the potassium in the 20 t FFB. Even with full normal recycling, there was an annual shortfall of 142 kg K/ha. Hence, about 1 kg K/palm per year has to come from depletion of the soil, or from fertilisers. The equivalent results for the other elements were 16.4 kg P and 38 kg Mg/ha per year.

Ng *et al.* (1999) concluded from other calculations that Munchong soil would supply just about enough nitrogen for 20 t FFB on a continuing basis, but not for the 30 t/ha level. The exchangeable potassium in Munchong soil is about 600 kg/ha, so it would be depleted in 5–6 years if no fertilisers were supplied. In practice, rapidly increasing potassium deficiency would sharply decrease the FFB yield before then.

11.6.2.3 Detailed applications: nutrient demands

This basic approach is expanded in the full INFERS model, which deals with all three 'demands' (Fig. 11.1; see Section 11.1.2). In Fig. 11.18 Kee *et al.* (1994) state all the main factors to be taken into account. This is not exactly the same as the scheme used as a central

Table 11.16 Distribution of potassium in various components of the oil palm ecosystem on five soil types

Components	Selangor series		Briah series		Munchong series		Kuantan series		Malacca series	
	Control	Manured	Control	Manured	Control	Manured	Control	Manured	Control	Manured
Total palm	1,428 (92)	1,906 (123)	1,395 (73)	2,104 (111)	488 (30)	1,793 (112)	602 (48)	1,298 (104)	430 (32)	1,176 (87)
Frond heaps	59	56	54	17	9	24	9	31	16	38
Interrow vegetation	25	25	8	19	19	7	5	7	1	3
Total K in soil	9,944	9,564	13,120	13,358	360	614	1,143	2,153	4,234	4,641
Exchangeable K in soil	958	1,150	1,527	2,917	161	253	261	449	238	333
FFB (per year)	140	157	120	144	60	111	71	108	73	98
Pruned fronds (per year)	160	269	125	182	22	195	40	141	52	144
Male inflorescence (per year) ^b	na	16.1	na	na	na	na	na	na	na	na

^aAt 138 palms/ha; others at 148 palms/ha.^bFrom Ng and Thamboo (1967).

(): average immobilisation in palms per year.

na: not analysed.

After Teoh and Chew (1988b).

concept in this chapter, where the processes of growth demand, deficiency demand and environmental demand are separated, although the practical result may be little different. The most important difference is that Fig. 11.18 does not specifically mention that it may be necessary to increase the soil nutrient concentration in correcting a deficiency, which is an essential part of nutrient management.

Equation 11.2 can be written in an approximate form for the whole palm, i.e. growth demand and deficiency demand, omitting environmental demand. The summation of the nutrient uptake over a growth period $t_2 - t_1$ is not greater than

$$\frac{(X_2 - X_1)W_1 + (W_2 - W_1)X_2}{X_2W_2 - X_1W_1} = \quad (11.10)$$

where N is nutrient amount, X is mean nutrient concentration of a plant and W is dry matter weight, all at times t_1 and t_2 . W_1 is known, $W_2 - W_1$ including FFB yield can be estimated for the year ahead, X_1 is the existing mean concentration throughout the palm, and X_2 is the mean concentration that it is aimed to reach during the year. Soil changes must be added to this.

Four basic types of information are available to check the results of this process (Kee *et al.*, 1994).

- Leaf analyses are used to calculate the composition of the whole palm and its components. These are

also used to check the nutrient status of the palm against leaf composition norms at the beginning and end of the year.

- Soil analyses are used to calculate the changes in composition during a year, and the amount of nutrient stored.
- Nutrient ratios in the leaves are used to check possible imbalances in nutrients.
- Relevant fertiliser field experiment results allow the optimum leaf and soil compositions to be confirmed.

INFERS contains a complex calculation series, and only an outline of the current method is given here (Goh, K.J. pers. comm., 2001). The steps are as follows.

1. *Nutrient demand of the canopy*: In principle, there is no demand if the canopy is of constant size and composition, as the fronds recycle their nutrients back into the palm directly, and via the soil. However, the canopy grows for the first 8 years or so, and any increase in weight, or change in composition, as determined from the dimensions of the frond (Corley *et al.*, 1971b) and the composition of the pinnae, is determined through a series of equations. The dry weight of frond 17 is obtained from Corley *et al.* (1971b) (Section 4.1.3.2), which uses the dimensions of the frond petiole, and the N in frond 17 from the dry weight and the % N in the pinnae. Corrections may have to be applied depending on the sampling technique.

An amended equation has to be applied to palms younger than 18 months.

2. *Nutrient demand of the trunk:* A similar method is used to determine the demands of the trunk. Equations have been established for the trunk density, and its volume is easily calculated from height and diameter measurements (Section 4.1.3.3). The trunk N concentration is given by:

$$\text{Trunk N\%} = 1.369 - 0.117 (\text{palm age, years}) \text{ up to 8.5 years old} \quad (11.12)$$

$$\text{Trunk N\%} = 0.351 \text{ above 8.51 years}$$

The trunk N content is then found from the concentration and the weight. The increase in the N content between times t_1 and t_2 can then be found by difference.

$$\begin{aligned} \text{Trunk N growth demand} = \\ \text{Trunk N\%}_{t_1} (\text{Trunk W}_{t_1} - \text{Trunk W}_{t_2}) \end{aligned} \quad (11.13)$$

where % N is a constant.

$$\begin{aligned} \text{Trunk N deficiency demand} = \\ \text{Trunk W}_{t_2} (\text{Trunk N\%}_2 - \text{N\%}_1) \end{aligned} \quad (11.14)$$

3. *Nutrient demand of the roots:* It has been found better to calculate the root dry weight from the root/shoot ratio, determined from the empirical equation:

$$\text{Root:shoot ratio} = 1.92 (\text{age, years})^{-1.11} \quad (11.15)$$

The other calculations follow the same path, with the N concentrations in the root also being a function of age.

4. *FFB nutrient demand:* It is assumed that the concentration of nutrients in the FFB is not affected by age, and remains constant. However, if the fertiliser regime changed, there may be a change in the concentration, as noted above. The constant in the equation varies between inland soils and coastal soils, e.g.

$$\begin{aligned} \text{Nutrient demand by FFB} = \\ \text{FFB yield} \times \text{Nutrient concentration} = \\ \text{FFB(2) kg} \times 3.195 \end{aligned} \quad (11.16)$$

where FFB(2) is the yield at the final fertilised rate.

The other inputs are the climate (which will already have been considered within ASYP for yield effects), the existing nutritional status of the palms (from plant or soil analysis), and the block history of treatment and yield in the past. Where experience has been gained of the fertiliser uptake efficiency (Section 11.6.1.4) on relevant soil types from existing fertiliser experiments, this is included, although this will depend on the soil nutrient

status and fertiliser quantity, even within the same soil series.

11.6.2.4 Detailed application: environmental losses

Soil erosion and runoff losses: This uses the model of Morgan *et al.* (1984) that was developed for Malaysian conditions. This calculates the water phase runoff on the basis of the rainfall characteristics, and some soil characteristics such as the bulk density and the moisture content. In the next step, the erosion losses are calculated from the runoff rate, a crop cover factor, the rate of splash detachment and the steepness of the slope. This model was tested on three Malaysian runoff field experiments between 1992 and 1997. The correlation between annual erosion and runoff calculations and measured data was $r^2 = 0.90$ and 0.84 , respectively. This is very satisfactory, but it cannot predict single monthly data well. These results are used to calculate the nutrient loss, by simply multiplying the loss of topsoil weight by the extractable nutrient concentrations. This calculation is the correct one to make, but it may lead to overfertilising in the short term, if there is still a sufficient depth of topsoil remaining. The concentration in the runoff water has always been found to be small, and is probably trivial in the nutrient balance.

Soil leaching: This loss is calculated from the model of Burns (1974), which is a simple multilayer chromatography-type model that transfers water from layer to layer (Tinker and Nye, 2000). It allows downward movement by leaching and upward movement following evaporation. The latter is probably of little importance in high-rainfall zones, and it may be possible to find more recent relevant models.

Soil nutrient demand: As noted above, if there is a deficiency of a nutrient, the soil content must be increased permanently. So far, INFERS does not calculate this explicitly, although it may be allowed for in advisers' judgements. The problems were discussed in Section 11.6.1.

The nitrogen in rainfall is allowed for, the average concentration in Malaysia being 0.85 mg N/l , and rarely exceeding 3 mg/l , which is about 60 kg/ha per year.

The output from INFERS is (Kee *et al.*, 1994):

- the new predicted yield (based on ASYP)
- the new fertiliser recommendation appropriate for the predicted yield
- a new nutrient balance for the field
- a statement of the nutrient supply that can be taken from the soil, either over a limited period or indefinitely.

Table 11.17 Surface runoff expressed as percentage of total rainfall

Ref.	Location	Soil/slope	Palm age (years)	Mean annual rainfall (mm)	% Runoff	Notes
Kee and Chew (1996)	Lepan	Musang	18	2,748	28.4	148 palms/ha
	Kabu	7–7.5°				
	Balau	Rengam	14	2,523	24.6	148 palms/ha
	Sri Kunak	6.9–7.1°				
		Batang				
		5.2–6.2°	13	1,979	22.9	120 palms/ha
Maene <i>et al.</i> (1979)	Gomali Estate	Durian	11	1,426	20.2	Palm rows
					30.6	Harvest path
					2.8	Fronde heaps
					18.5	Overall mean
						148 palms/ha

After Kee *et al.* (2000).

The actual computations by which these values and other information are derived and integrated with the nutrient budget have not all been published yet, and the most recent descriptive guide to the procedure is AAR (1999), with a brief general description in Kok *et al.* (2000).

11.6.2.5 Supply from different soil types in INFERS

The possibility of not replacing some nutrients fully has been discussed earlier. INFERS does not in principle aim to deplete soil nutrients, but soil supply can be assumed during replanting or planting from forest, and in the following special situations:

- peat soils (fibric to hemic; see Section 3.4.3.7) may produce a large flush of nitrogen from the second year after planting onwards, owing to mineralisation of the peat, and the nitrogen application should be reduced to avoid N/K imbalance.
- In coastal soils or other young alluvial soils the calcium and magnesium are usually high, and no magnesium addition is needed.
- The residual value of large dressings of phosphate rock and ground magnesium limestone (Goh *et al.*, 1998) can be up to 3 years' demand (Section 11.9.2.3), and these elements can probably be omitted in such cases.

The computations of nutrient balance are still open to error, as experience needs to be gained in various directions. Thus, to prevent overmanuring, INFERS has a set maximum of 1180 g N/palm per year.

11.6.2.6 General research to support INFERS

INFERS brings together information from a number of research projects that increased knowledge of the terms in the nutrient balance. Thus, the dynamics of potassium behaviour in the palm has been elucidated by Teoh and Chew (1988b) on fertiliser experiments on five different soil series, building on the work of Ng and Thamboo (1967) and Ng *et al.* (1968) (Table 11.5). As yet, there are no equally detailed data for other nutrients. The nutrient losses by runoff and erosion have been quantified (Kee and Chew, 1996) on three different sites, in Sabah (Batang series), Selangor (Rengam series) and Kelantan (Musang series), building on work by Maene *et al.* (1979). Runoff and erosion are highly site specific, and three investigations cannot possibly cover the whole subject (Table 11.17) (Kee *et al.*, 2000), but from the amount of fertiliser, the soil type and slope, the dryness of the soil, and the size of the first rainfall, the fertiliser lost can be reasonably estimated. This information has been developed into an expert system in the AA AeGIS system.

Work on the volatilisation of ammonia after spreading urea, and its dependence on recent rainfall is used (Table 11.18) (Chan and Chew, 1984) (Section 11.7.4). The uptake of nutrient in the ground cover may also be important during the early growth of the palm (Han and Chew, 1982; Tan and Ng, 1982; Teo *et al.*, 1990), with contents of at least 200 kg/ha of nitrogen and potassium during the first few years. Later, the cover dies back because of lack of light (Section 10.1.2.3), and the supply to the palms then should be taken into account. Leaching losses have been used as measured by Foong

Table 11.18 Urea volatilisation losses as percentage of application on several soils under oil palms

N rate (kg/ha)	Silty clay soils		Sandy clay soil		Sandy clay loam	
	At 3 days	At 7 days	At 3 days	At 7 days	At 3 days	At 7 days
250	29	29	27	38	35	42
500	38	42	35	45	38	48

After Chan and Chew (1984).

Table 11.19 Leaching losses of nutrients measured in a lysimeter, as percentage of applications

Palm age (years)	Leaching losses as % of applied nutrients			
	N	P	K	Mg
1–4	16.6	1.8	9.7	69.8
5–8	1.2	1.6	2.5	11.5
9–14	3.0	1.5	2.9	15.5

After Foong (1993).

(1993) (Table 11.19) (Section 11.7.4). For mature palms, this leaching loss was taken as 3.0, 1.5, 2.9 and 15.5% of N, P, K and Mg fertiliser additions, respectively, although rigid assumptions based on a single set of experiments are highly suspect.

These models have undergone testing (Kee *et al.*, 1994; Kok *et al.*, 2000) (Table 11.20) using fertiliser experiments of varying design on five different soil types. The predicted yields from ASYP agreed well with the yields when the palms were given the computed fertiliser rates. After reversing the assessment, so as to predict the fertiliser necessary to give the measured yields in the experiments, good agreement was also found between the actual and the predicted fertiliser rates (Table 11.21) (Kee *et al.*, 1994). In a few cases there was no response to a nutrient where that was expected, but this can occur if the soil contributes nutrient that was not allowed for. Other special factors such as high phosphate adsorption (fixation), immobilisation by ground cover, and a consideration of whether the proposed fertiliser schedule will lead to nutrient imbalance later, need to be considered.

Kee *et al.* (1994) also further described the expert system 'Best months and timing and allocation of fertiliser', which is based on an assessment of the effect of rainfall on fertiliser loss (Section 11.7.4.1). The AA AeGIS system contains a large site database. It is therefore able to

put out the recommendations in a site-specific way and with the attachment of appropriate maps.

11.6.3 French systems

These fertiliser prediction methods are based on leaf analysis, developed from the early work by Prevot and Ollagnier (1954, 1957). The French groups have been responsible for a large part of the advances made in leaf analysis. The principle used by CIRAD (Centre de Co-operation Internationale en Recherche Agronomique pour le Developpement) is to put down fertiliser factorial field experiments on important soil types within which the processes of mineral nutrition are basically similar (Caliman *et al.*, 1994). The results were often fitted to a Mitscherlich equation (Section 11.3.1), and the economically optimum rate (EOR) was determined from the fitted curve. Leaf analyses were carried out on the trials, and response curves of the leaf analysis results were used to determine the critical level corresponding to the EOR.

An interesting method for the longer term adjustment of fertiliser rates is to use an equation for the fertiliser rate that causes the leaf analysis result to converge progressively to the critical level. The equation is:

$$D_n = D_{n-1} + a(N_{n-1} - N_n) + b(N_c - N_n) \quad (11.17)$$

where D_n is the application rate in year n , N_n is the leaf nutrient level in year n , N_c is the critical level, and a , b and c are constants. The fertiliser rate in year n is therefore adjusted from that in year $n - 1$, in accordance with the change in the analysis value and the difference from the critical value. Finally, $N_n = N_{n-1}$ and $N_n = N_c$. Tables are drawn up from this equation from which rates can be read off. Much attention is paid to the accuracy of the analyses and procedures. The principles are thus similar to general leaf analysis (Section 11.4.3). A feature of this work has been an uncertainty about whether to use single-element values or ratios. Thus,

Table 11.20 Comparison of the difference between the yield predicted by INFERS and the actual yield, on 51 individual treatment combinations in six trials, each on a different soil type

Trial	Soil type	Total no. of cases	% Yield difference from actual					
			<5	5–10	10–15	15–20	Min.	Max.
1	Akob	10	0	6	3	1	6.2	15.9
2	Briah	8	5	3	0	0	2.2	6.6
3	Lunas	8	8	0	0	0	–0.7	3.8
4	Sogomana	8	8	0	0	0	0.1	–3.1
5	Musang	9	0	5	3	1	–5.3	–18.5
6	Bernam	8	0	5	2	1	–7.7	–16.5
Total		51	21	19	8	3		

Yield difference (%) = (Actual – Predicted yield)/Actual yield × 100
 After Kee *et al.* (1994).

Table 11.21 Difference in weights of the predicted fertiliser required by INFERS from the actual rate of fertiliser applied for the treatment combination giving predicted yields, in six soil types

Trial no.	Soil type	Total no. of cases	Fertiliser N rate Difference as kg AC		Fertiliser K rate Difference as kg KCl	
			<0.25	0.25–0.50	<0.25	0.25–0.50
1	Akob	10	4	6	9	1
2	Briah	8	7	1	8	0
3	Lunas	8	8	0	8	0
4	Sogomana	8	7	1	8	0
5	Musang	9	4	5	9	0
6	Bernam	8	0	8	7	1
Total		51	30	21	49	2

Difference (kg) = (Predicted – Actual fertiliser rate) expressed as kg ammonium chloride (AC) and potassium chloride (KCl)/palm.
 After Kee *et al.* (1994).

Tampubolon *et al.* (1990) found that the ratio P/N in the leaflets was the best criterion for predicting phosphate deficiency. They also found a relationship between the critical levels of phosphorus and nitrogen:

$$P_c\% = 0.0487 N_c\% + 0.039 \quad (11.18)$$

The effect of changes in N in the leaflets thus appeared both directly on N status, and also on the changes in the P status. The critical limit for Mg was 0.15%, but there was a chance of a response up to 0.20% dry matter (Dubos *et al.*, 1999). Work by CIRAD has found that different genotypes may have specific nutritional properties, e.g. one cross (L2T × D10D) had lower potassium and higher magnesium contents than another cross, when grown on the same soils (Caliman *et al.*, 1994) (Table 11.10). The implication of these results is not yet clear.

11.6.4 Foster system (PORIM fertiliser recommendation system)

11.6.4.1 General structure

These systems were developed by Foster and his associates during his work at MARDI and later at PORIM in Malaysia. The work has been wide-ranging and innovative, and has generated a large number of published papers, so it requires care to understand it fully. This literature mentions four methods (Foster, 2002), but the work involves two basic approaches, which for the purposes of discussion here will be called Foster A and Foster B systems. These are (A) the use of site characteristics to determine yield without fertiliser, fertiliser need and the efficiency of response (dY/dN) to fertiliser

(Foster *et al.*, 1986; Foster, 1995), and (B) the use of leaf analysis data to determine the palm nutritional status and fertiliser need (Foster and Chang, 1977; Foster *et al.*, 1988c). The use of soil analysis has been examined (Foster and Tarmizi Mohamad, 1988; Foster, 2002), but has been abandoned except for certain measurements used in systems A and B. It may become possible to combine the A and B approaches, if site characteristics are used to correct the leaf analysis methods. In essence, the leaf analysis would then determine the nutritional status of the palms, and the site and soil characteristics would determine the efficiency of response to fertiliser and the optimum economic dressing (H.L. Foster, pers. comm.). This would be an important development. The systems are in total statistically and physically complex, and a useful oversight of the whole work is in Foster (2002). They share the characteristic with INFERS that they aim to integrate the main methods of understanding the nutrient state of palm fields. It needs to be emphasised that both the A and B systems assume that the palms are in a near-steady state, so that the composition of the palm and the soil are approximately constant. For this reason, the deficiency demand does not appear explicitly in these systems (Section 11.3.2.1). However, if the aim is to predict and implement a higher yielding fertiliser regime, then this demand would have to be met in the move to the new steady state. This lack of clarity about the real state of a field experiment may cause problems.

11.6.4.2 Foster system A: yields without fertiliser

A classical method of fertiliser need prediction is to find a fertiliser experiment with characteristics that are very similar to those of the field being examined, and then to extrapolate directly from this experiment to the field. This method may not work because no such fertiliser experiment may exist. It is also recognised that this is a crude method (Foster, 2002), because experiments may give different responses even on the same soil series and with some similar characteristics (Foster *et al.*, 1986).

The improved method of using such information (Foster system A) combines site characteristics from around 50 factorial fertiliser experiments in Peninsular Malaysia (Foster *et al.*, 1985a). Most of these included three levels of nitrogen and potassium, and two levels of phosphorus and magnesium. System A starts with a series of equations that allows prediction of yields without N and K fertiliser (Foster *et al.*, 1985a), in the presence of ample other nutrients, based purely on site and climate characteristics. As with all such statistical systems, the equations are only valid within the region

Table 11.22 Example of list of important site characteristics for a granite-derived soil in Malaysia, with typical scores

Characteristic	Score
Palm age (years)	12
Planting density (palms/ha)	148
Soil drainage class	0
Soil consistency class	0
Slope class ^a	0.5
Soil organic matter (%)	2.5
Silt (%)	6.0
Extractable K (cmol/kg)	0.06
Total extractable bases (cmol/kg)	1.20
Annual rainfall (mm/year)	2,000

^a0: no limitation; 1: moderate limitation; 2: severe limitation. After Foster (2002).

in which the experiments have been performed, and so far they are only available from past work of public and private organisations on inland and coastal soils in Malaysia. A large series of local factorial fertiliser experiments is thus a prerequisite of applying the system in any other region, and in no other region is this yet available. Work is in progress to gather information in Indonesia (H.L. Foster, pers. comm.).

The different characteristics required for system A are given in Table 11.22, for estimating yields without fertiliser and the response curves to fertiliser. These include four site/soil survey measurements and four soil analysis measurements, which contain eight variables, although some of these are not used independently. Most of these are made on soil samples collected at 0–30 cm depth where fertiliser has been applied, although extractable (exchangeable) potassium, calcium and magnesium are measured on soil from the avenues at least 6 months after the last fertiliser application, on the assumption that this area is not manured. As in other cases, the varying method of physically applying fertiliser to oil palms is potentially problematic.

The system of equations first uses the characteristics to predict the yield without nitrogen and/or potassium fertiliser, but with non-limiting levels of other fertilisers (Foster *et al.*, 1985a). This determines the starting point of the final response curves that include the data from all the experiments. The environmental characteristics that affect yield without fertilisers are slope, topsoil structure, consistency of soil, drainage, water table depth and impedance to root growth. Because of the different mineralogy of the coastal and inland soils, these were treated separately, and the important characteristics are rather different. Almost

all of the trials were carried out in states with annual rainfall around 1600–2400 mm, reasonably well distributed throughout the year. The rainfall may be used to make the predictions instead of the drainage, if other factors are similar.

The equations relating yield without N or K fertiliser to site characteristics, using all data from the existing fertiliser experiments, are in the form (Foster *et al.*, 1985a):

$$\text{Yield} = 22.5 - 2.720 X_4 + 9.662 X_6 + 0.0026 X_8 \quad (11.19)$$

which is for alluvial (coastal) soils. The X terms are, in order, drainage, extractable soil potassium and average annual rainfall. The r^2 for four groups of equations, for two soil groups and zero N or zero K fertilisers, were 61.2, 73.9, 52.6 and 72.3, respectively, so the final relationship between measured yields and predicted yields when these are controlled by the soil supply of either N or K was reasonably good. To predict yields with neither N nor K fertiliser an equation with an NK interaction term is used. The importance of these equations is that they fix the zero point on the yield–fertiliser response curves.

11.6.4.3 Foster system A: field experiment data, yield response and site characteristics

The main fertiliser requirements for mature palms are for nitrogen and potassium on inland soils and for nitrogen on coastal soils. System A for predicting fertiliser need from field experiments is given in Foster *et al.* (1984b, 1985a, 1986). It involves site characteristics and the prediction of yield without fertilisers, as explained above. One conclusion was that factors controlling FFB yields without nitrogen or potassium (i.e. depending on soil N or soils K only) were mainly variable characteristics (extractable potassium, drainage level, etc.), whereas the efficiency of the response (FFB/kg nutrient) was related to permanent characteristics (slope, texture, etc.) and the factors affecting fertiliser recovery. Some factors are themselves related, e.g. rainfall and drainage conditions, so that rainfall may be used as a simpler alternative to drainage. In some cases the importance of a factor is easy to explain [e.g. Soil K/(Total exchangeable cations) and extractable potassium are important for potassium nutrition]. The effect of silt on potassium nutrition is difficult to explain, and it may be that the soil was insufficiently dispersed for the Boyucos hydrometer method employed, as organic matter was not removed. In that case much of the silt may really have been aggregated clay.

In next paper Foster *et al.* (1985b) aimed to calculate the responses to nitrogen and potassium fertilisers, and the resulting maximum yields. First, a yield response equation with linear, quadratic and interaction terms (i.e. $a + cN + cN_2 + cK + cK_2 + cNK$, etc.) was fitted to all the plot yields within a factorial fertiliser experiment, giving smoothed response surfaces based on corrected plot data. It will be recalled that the quadratic model tends to overemphasise the peak in yield and the level of fertiliser at which it occurs (Section 11.3.1).

It is difficult to combine the results from a number of field experiments, except in the rather crude way of averaging the results at each rate of fertiliser. Here, it is postulated that there is a single theoretical response curve, but that as the natural supply of a nutrient at each site is different, it is not possible simply to plot them all together. This problem was avoided by plotting the yields on the exponential (Mitscherlich) (Section 11.3.1) (Equation 11.3b) model, which has no specific zero nutrient point, using the site characteristics as modifying constants. From the quadratic curves, the increase in yield from one rate to the next was found, as dY/dF , each one identified with the mean yield Y over that interval. The individual trial results were plotted as in Equation 11.20, which expresses the relation between the yield Y and the fertiliser rate F as a differential (Foster *et al.*, 1985b):

$$dY/dF = a + bY \quad (11.20)$$

Here, the constant a is determined by the environmental factors, which influence the efficiency of crop recovery of fertiliser. This can be quantified by fitting a response equation, with $a = p + qS_1 + rS_2$, etc., so that:

$$dY/dF = p + qS_1 + rS_2 + bY \quad (11.21)$$

where p and q are constants, and S terms are the various site characteristics. The concept is that all experiments on one soil series have the same underlying relationship between Y and dY/dF , but that these are modified by the site characteristics. The amount of nutrients present (soil and fertiliser) determine the yield, and the yield determines the amount of response to an added rate. These equations were fitted to the data from each experiment, for nitrogen and potassium separately, with dY/dF being the slope of the line from one response point to the next, and Y being the midpoint yield. In all, 23 different measured characteristics were tested in this equation (Foster *et al.*, 1984b). The fitted equations in this paper show the following characteristics as being significantly related to yield: average slope, soil drainage, soil % clay, soil % silt, soil total extractable (exchangeable) cations, average annual rainfall, leaching intensity

at 2 months and leaching intensity at 3 months (after a fertiliser application). Each trial thus produces a separate curve, though based on a common equation.

This equation (11.21) can be integrated to a simple exponential:

$$(\ln[p + qS_1 + rS_2 \cdots + bY] + b_4S_4 + b_5S_5 + \cdots) = (bF + c), \quad (11.22)$$

where c is another constant, which represents the yield without fertilisers. The value of this is known for each experiment from Equation 11.19. Equation 11.22 contains the relationship of Y and F , and can be used to plot graphs such as Fig. 11.19. It should be noted that the exponential form is a convenient model, as it allows different experiments to be combined, but it was chosen for empirical reasons. The exponential model never reaches either a peak or a plateau, so it is not possible to define a maximum yield, although it may be possible to predict an EOR after deducting the fertiliser cost (Section 11.6.3).

Foster (1995) discussed the use of this site factor system, and showed data of oil palm yields (Foster, *et al.*, 1986) supporting the system, with correlations between observed and predicted yields with fertiliser of up to $r^2 = 0.72$. Chew *et al.* (1992) queried the system because it depended on statistical relations, and not on a basic understanding of the underlying mechanisms, and seemed to predict very high fertiliser requirements in some situations. Foster (1995) noted that it was advisable to use leaf analysis to fine-tune the system, and also that planting materials had greatly improved since the trials used were planted between 1960 and 1980, so

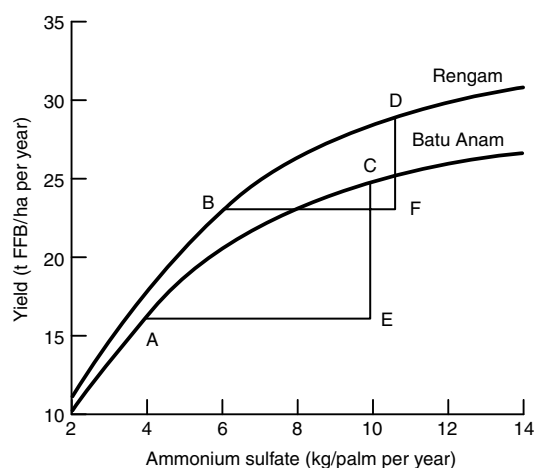


Fig. 11.19 FFB yield response to nitrogen in Malaysia, plotted as exponential graphs. (After Foster, 2002.) AC and BD are the response curves for two particular experiments.

errors were possible at high yield levels. A correction of 5% brought the observed and predicted data closer. This suggests that new generations of field experiments may be needed at intervals to take account of this genetic improvement. Foster also showed how the system could be adapted to give the different risks of return for the last kilogram application of fertiliser, so that the optimum fertiliser dressing was defined in terms of economic risk. As Foster (2002) says, such complex systems could only be developed where a large number of reliable multifactor fertiliser experiments have been laid down and have given extensive data.

11.6.4.4 Foster system B: leaf analysis

Later, a leaf analysis programme was arranged to give additional verification of the results (Foster, 1995, 2002). Foster and Chang (1977) found good statistical relationships between leaf analyses, carried out in the traditional way, and FFB yield. The highest yield appears to be critically dependent on the exact leaf composition, as shown on a contour map (Fig. 11.20) (Foster, 2002). This extreme criticality seems to be an important point, and suggests that very high yields demand extreme precision in leaf composition. The general concept that the level of a deficient nutrient in a plant becomes more and more critical as other deficiencies are eliminated, and the yield level of the crop increases, is well known

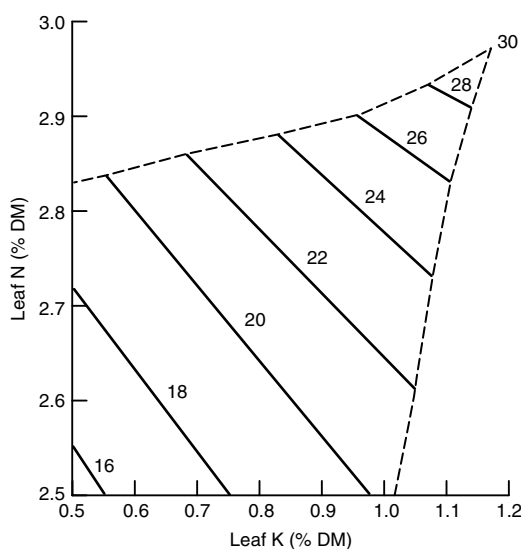


Fig. 11.20 Yield isoquants (lines of equal yield) for nitrogen and potassium concentrations in the leaves in a trial on a granite-derived soil in Malaysia. (After Foster, 2002.)

in foliar analysis work (Walworth and Sumner, 1988). Foster considered that the oil palm does not have luxury consumption, so that any increase in leaf concentration must be linked to a yield increase. The implication (H.L. Foster, pers. comm.) is that each element has a maximum concentration, and when all elements reach this highest value, then maximum yield (in relation to all nutrients) has been reached.

On the other hand, if more than one element (say potassium) was limiting, there will be no single correlation between the % leaf K and the yield as long as potassium is deficient, but at the optimum yield for potassium, whatever this is, the K level is always 1.15%. In general, the greater the gap between 1.15% and a lower potassium level, the more fertiliser that was needed, on a single soil type. The overall conclusion (Foster, 2002) was that 'leaf analysis is required to determine the extent of a nutrient deficiency, and site properties must be identified to estimate the amount of fertiliser required to correct the deficiency'. This is an excellent general approach for determining the deficiency demand (Section 11.6.1.3), although the growth demand is only brought in indirectly (Section 11.6.4.1).

Foster (2002) rightly concluded that leaf analysis alone is only useful for situations where the nutrition of the palms is not far from optimum, and noted that it is essential to follow the procedures for leaf sampling, analysis and interpretation precisely if these methods are to work. Where there are pronounced deficiencies, or extreme environmental factors, leaf analysis alone is not sufficient and the influence of site factors on fertiliser efficiency must be taken into account. This occurs, for example, where phosphorus or potassium fertilisers are applied to highly buffered soils, or in very wet or very dry conditions. The fertiliser may then have low uptake efficiency because little of it remains in, or enters, the soil solution, or because much of it is washed away or leached.

11.6.4.5 Total leaf cations in leaf analysis

A major innovation in the Foster system is the use of total leaf bases (K, Ca and Mg) as an internal reference point for the various nutrients (Foster, 1995). (They should be called total leaf cations, as they are not bases in modern chemical terminology. They are called TLC from here onwards, in agreement with Foster.) There are analogies in this to earlier work, such as the activity ratio and exchangeable cation approach of Tinker (1964b) in soil analyses (Section 11.5.3), and the widespread ideas of ratios as more important variables than absolute concentrations in leaf analysis generally (e.g. N/P) (Section 11.4.3). However, it has been more usual to balance single cations with total cations; the unusual part of Foster's work was to balance the nitrogen concentration against all of the cations, and the underlying physiology of this is unclear. The TLC was found to be well correlated with the water-holding capacity of the soils on which the palms were growing, which is also difficult to explain in general. However, in the specific Malaysian situation the water-holding capacity of the soils is largest on the coastal soils, which also contain most calcium and magnesium, so possibly the correlation arises from this fact, if it is assumed that leaf Ca and Mg are related to the soil cations.

The calculation of TLC (Foster, 2002) is as follows, all elements being compared in moles:

$$\text{TLC (cmol/kg dry matter)} = \frac{[\text{Leaf K}/(39.1) + \text{Leaf Mg}/(24.3/2) + \text{Leaf Ca}/(40.1/2)] \times 1000}{\text{Total}} \quad (11.23)$$

This development started from the fact that the correlation of leaf potassium and yield on coastal soils was much better when soil exchangeable calcium was included in a ratio with the leaf concentrations, and this is correlated with TLC (Table 11.23). Including TLC in

Table 11.23 Typical soil exchangeable cation contents and oil palm leaf nutrient concentrations in four regions of Malaysia and Sumatra

Soil region	Exchangeable cation (cmol/kg)					Leaf	
	Ca	Mg	K	Total	Ca/total	Ca (%)	TLB (cmol/kg)
Inland (Malaysia)	0.88	0.43	0.33	1.64	>0.5	0.75–0.90	80–90
Volcanic (PNG)	8.10	1.55	0.24	9.89			
Coastal (Malaysia)	2.04	2.73	1.82	6.59			
Volcanic (Sumatra)	0.98	0.72	0.42	2.12	<0.5	0.40–0.60	60–70

After Foster (2002).

the calculations automatically allows for some of the site characteristics (Foster, 1995). The final method for Malaysian inland soils (Foster, 2002) showed the effect of changes in TLC (Fig. 11.21). A quadratic equation, containing the single leaf nutrient and the TLC value, accounted for quite large percentages of the variation in FFB yield response to single fertilisers on inland soils (Foster *et al.*, 1988c) (Table 11.24). The DRIS index (Section 11.4.3) was tested at the same time, but was generally inferior to these results in accounting for yield variation.

The main differences between inland, coastal and volcanic soils may be connected with their calcium

contents (Section 11.4.6). Exchangeable calcium is often correlated with exchange capacity, which is correlated with clay and organic matter content, and also with pH. These relationships between soil variables are very well known, but the strong interactions with leaf composition found in this work are probably novel.

The methods discussed here allow the optimum leaf levels corresponding to the maximum yield to be determined, except in some cases on coastal soils. This, however, assumes that the data refer to palms with only one deficiency. In practice, the most deficient nutrient needs to be detected and corrected first, and others in subsequent years, by a stepwise technique (Foster, 1995).

This total approach is interesting and innovative, and certainly shows successes. However, like DRIS, it is a complicated, computationally based system, the details of which are sometimes difficult to understand in biophysical terms, and the inner workings of which are therefore rather opaque. Most of the available Malaysian field experiments provided data that were used in determining the statistical relations on which the method is based, and hence there were few fully independent field experiments that could be used for validation, although the methods are now being applied in Indonesia and PNG. Foster (1995) notes that the system may sometimes appear to fail because unexpected site characteristics will have an influence that is not accounted for. A programme of new experiments with a sufficient number and range of nutrient rates to define response curves was planned by PORIM (MPOB) some years ago in order to validate this system, but it has not yet become operational.

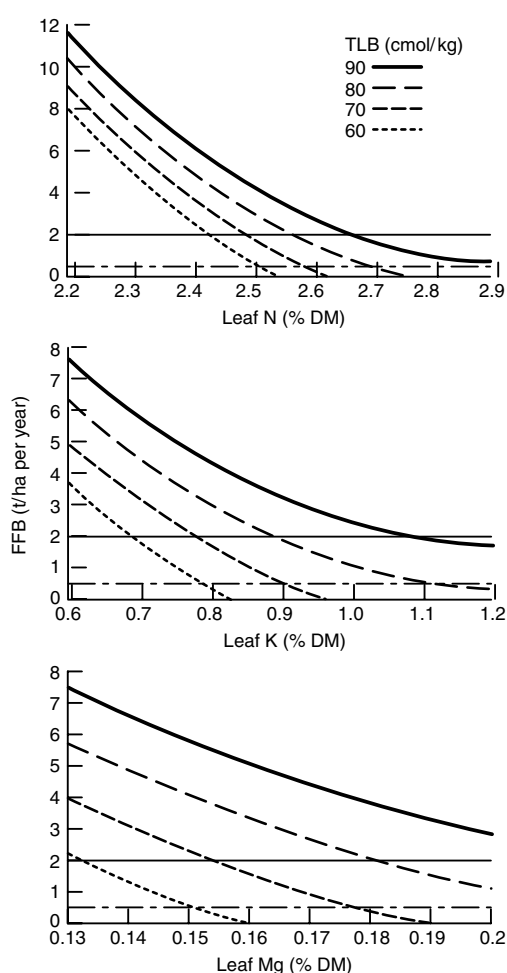


Fig. 11.21 FFB response to fertiliser as a function of leaf nitrogen, phosphorus and potassium concentrations at different levels of total leaf cations. (Foster, 2002.)

11.6.4.6 Soil analysis systems

Foster (2002) also discussed soil-based prediction systems. Ideally, samples from typical unfertilised areas are needed, to measure or predict unfertilised yields, but very few commercial fields have such areas (Section 11.6.4.2). Even if the results from analyses of fertilised soil could be used to define a position on the curves in Fig. 11.19 (Foster, 2002), in practice the error in sampling a fertilised field is too large (Foster and Chang, 1977). The problems arising from the use of placed fertiliser have already been discussed (see Sections 11.2.1.2 and 11.8.3), and Foster (2002) considered that at present these remove any practical possibility of a soil-based prediction system, which otherwise seems theoretically possible.

Table 11.24 Percentage variation (% R^2) in FFB responses to individual fertilisers accounted for by different leaf nutrient indices

Leaf nutrient index	N		P		K		Mg	
	Inland	Coastal	Inland	Coastal	Inland	Coastal	Inland	Coastal
Nutrient (%)	41.1	26.1	47.5	0.3	37.8	3.1	15.7	0.2
Critical value (%) (P) – Nutrient (%)	35.7	34.4	46.8	1.5	42.4	3.1	26.0	0.5
Critical value (%) (PS) – Nutrient (%)	26.9	30.0	61.8	0.2	43.5	32.2	22.1	1.2
DRIS index	38.8	30.5	55.5	2.1	53.5	0.6	12.8	0.5
DRIS index (PS)	14.3	21.9	41.5	0.1	51.5	30.3	23.0	2.5
TLC (%), Nutrient	51.0	38.7	38.1	4.4	57.1	0.2	16.0	0.1
Nutrient (%), Nutrient ² (%), TLC, TLC ²	63.3	47.8	76.4 ^a	4.8	63.5	2.0	48.6	3.7
Nutrient (%), Nutrient ² (%), TLC, TLC ² (PS)	67.6	55.4	79.4 ^a	12.8	68.1	35.1	69.2	3.8

P: calculated using palm data (age, density, TLC).

PS: Calculated using palm and site data (rainfall, silt, soil TEC).

^aIncluding leaf percentage Ca as an independent variable.

After Foster *et al.* (1988c). See original paper for further details.

11.7 RECYCLING AND LOSSES OF NUTRIENTS

11.7.1 Replanting and the nutrients in the old stand

The nutrient balance discussed before shows that at present the efficiency of fertilisers given to oil palms is low. Under Asian conditions (United Plantations) the total amount of fertiliser nutrients given to each palm over 25 years may be around 20 kg N, 15 kg P and 25 kg K (Xaviar, 2000). Fertiliser rates on inland soils are greater. All of this can initially be accounted for in FFB, storage in the palms or various losses. Yet the final output of oil and kernels will contain only some 15 kg N, 3 kg P, 5 kg K, 2 kg Mg and 1 kg Ca, assuming 20 t FFB and 5.5% kernel/bunch, and the concentrations of nutrients as given by Ng and Thamboo (1967). In the most narrow sense, the efficiency of the fertilisers, especially potassium, in relation to nutrients in the commercial output is disappointingly low (Ng, 1977; Tinker, 2000a).

The most important way of reducing costs in the industry is to improve the efficiency of the fertiliser applied. Part of the loss cannot be regained, if it is in runoff, erosion, leaching and volatilisation, and this must be minimised by better agronomy. Part of the loss may be recovered, because the wastes from the factory process, EFB and POME, may be recycled on to the palm fields, although the efficiency of the recycling is not 100% and there will always be some loss. The

largely ignored factor is the nutrients that are in the mature palm, especially in the trunk, at the time of felling (Fig. 11.4). Ng *et al.* (1968) gave the cumulative content of nutrients in a 15-year-old palm as about 4.3 kg N, 0.25 kg P, 8 kg K, 1.2 kg Mg, 1.8 kg Ca and 2 kg S. Teoh and Chew (1988b) gave rather larger values for potassium in 12 to 19-year-old palms, of about 12.8 kg K at 19 years of age on a Briah series soil (Table 11.5). Four out of their five sites gave a good relationship of age with potassium content, with an approximate addition of a little less than 1 kg K/year, assuming that accumulation started on average at 3 years old. Hence, this value for potassium content agrees well with that of Ng *et al.* (1968). Henson (1999c) calculated that the palms worked on by Teoh and Chew (1988b) had a negative nutrient balance of some 90 kg K/ha. However, Selangor soil is well known for its ability to release potassium, and this does not necessarily mean that the palms were potassium deficient.

There appear to be few published direct measurements of nutrient content at the time of felling, except those of Khalid *et al.* (1999a, c). They measured the nutrients in trees felled when a 23-year-old first rotation field was replanted, and found 642 (4.7) kg N, 58 (0.43) kg P, 1384 (10.2) kg K and 156 (1.1) kg Mg, all per hectare and (per palm). There will be some nutrients in the ground-cover plants, but this is relatively trivial under mature palms and can be ignored. These data agree reasonably well, although the potassium content may be rather low for a 23-year-old palm, assuming that

older palms continue to accumulate nutrients at the rate suggested above. These nutrients are valuable, and correspond to about 7 t of fertiliser in all.

The objective is to return the nutrients into the new stand that is growing up. Most replanting now follows zero-burn (see Section 8.3.2). The rate of breakdown of the residues will vary with the conditions, but the breakdown rate of the trunk is most important, because of its large mass and large nutrient content. It is now standard procedure to break the trunks down into chips (see Section 8.3.4), which decay more rapidly, within a few months. Part of the problem of utilising the nutrients in the old stand may be reduced by stopping the manuring programme for not more than 1 or 2 years before the actual replanting (Nazeeb *et al.*, 1995) (see Section 8.3.4.1), although Goh *et al.* (1994a) believed that the palm trunk contained enough potassium to sustain the yield of the palm for 2–6 years. Teo *et al.* (2000) pointed out that nearly all fertiliser experiments in Malaysia had been done on 5–15-year-old palms. They found that with 23-year-old palms on a Harimau series soil the withdrawal of potassium and nitrogen fertilising up to 44 months before felling reduced vegetative growth parameters and yield, yet there was no significant difference in the leaf nutrient levels. At the time of withdrawal of fertilisers the palms were well supplied with potassium and nitrogen. There was a reduction in the rachis potassium levels at the end of the experiment where potassium had been withdrawn, suggesting again that rachis potassium was more sensitive as a yield indicator than leaflet potassium. The authors concluded that it was cost-effective to continue to add fertiliser up to 1 year before felling, in fair agreement with Nazeeb *et al.* (1995). Contrary to the potassium results, nitrogen increased in the leaflets after fertilisers were withdrawn, suggesting that the need for nitrogen could be met from the soil reserves. Thus palms that are to be replanted will contain the normal quantity of nutrients unless fertilisers are withdrawn for more than 1 year.

Khalid *et al.* (1999a, c) applied four treatments immediately after felling: (1) complete removal of the palm refuse from the plots; (2) chipping and shredding of the trunks and fronds, and spreading the residue 3–4 m from the new planting points; (3) partial burning of the chipped trunks, about half being burnt; and (4) chipping of trunks and fronds as before, and pulverising of all the refuse afterwards. Full analyses were done on the soil at intervals over a period of 4 years (Khalid *et al.*, 1998, 1999a, 2000). The old palm avenues and the old frond pile positions were also sampled. Changes in total nitrogen were small and irregular, but the largest results were from under the old frond piles, as would

be expected. The low nutrient concentrations from the chipping/pulverising treatment are surprising, because the total residue was present, and in the most decomposable form. It is difficult to draw consistent and logical conclusions from the nitrogen data. The unexpected result for total phosphorus was that all the values, except under old frond piles, declined very sharply in the first 2 months, then rose massively from 4 months onwards in the pulverising treatment. Available phosphorus followed a similar pattern. It may be that badly distributed rock phosphate fertiliser before the experiment started has made the results difficult to explain.

The results for soil phosphate are also difficult to understand (Table 11.25) (Khalid *et al.*, 2000). Initially, all the values were identical, except for a higher value under the frond piles. Later, all values increased sharply, even on the complete removal plots, where there should have been no residues. With chipping/shredding, the K increase after 2 months down to 30 cm was four-fold, or about 750 kg K/ha. If the concentration in the no residue treatment is taken as the baseline, the amount is 470 kg K/ha. Both are credible figures, as more potassium may have travelled farther down the profile, but the large increase on the plot without residues is not easy to explain. The results for magnesium were similar, with values on the chipping/shredding plot increased four-fold in the topsoil, but only doubling in the subsoil. These changes correspond to about 90 kg Mg, which is reasonable. In this case, nitrogen showed no consistent changes, and those for phosphorus and potassium appear difficult to accept, at least towards the end of the experiment.

The question remains as to what happens to the nutrient in the old palms over the few years after felling. According to Fig. 11.2 (Ng, 1977), the amounts of nutrients in palms growing on inland soils would be, in the second year, N 75, P 6, K 120 and Mg 20, all in kg/ha. In the third year they would be N 230, P 15, K 210 and Mg 35 kg/ha. The uptake of magnesium to the end of the third year would account for the residue almost completely, but for potassium the amounts held in the young palm are only a small fraction of the amount in the old stand. The problem is indeed very important if larger uptake efficiency values are desired for the whole planting cycle.

11.7.2 Use of palm wastes

11.7.2.1 Use of empty fruit bunches

After the fruits had been stripped from the bunches in the factory, they were in the past often burnt, and the

Table 11.25 Changes in total phosphorus in soil at two depths and ten times in relation to replanting treatment

Month	Depth (cm)	Total P ($\mu\text{g/g}$) in Treatment ^a						LSD (0.05)
		C/R	C/S	P/B	C/P	O/A	O/FP	
0	0–15	263	263	263	263	263	150	–
	15–30	168	168	168	168	168	115	–
2	0–15	131	142	134	103	64	68	66.78
	15–30	99	80	94	75	54	60	ns
4	0–15	99	102	526	199	90	96	130.26
	15–30	77	75	371	140	75	64	74.89
6	0–15	171	206	506	306	145	136	122.87
	15–30	137	159	346	197	125	105	100.25
8	0–15	128	203	395	202	156	134	110.98
	15–30	104	138	252	124	137	116	77.07
10	0–15	151	233	283	200	132	119	106.49
	15–30	116	154	182	154	104	102	65.22
12	0–15	243	777	485	488	151	121	229.04
	15–30	197	329	246	302	132	108	103.48
14	0–15	139	191	223	230	109	116	77.17
	15–30	117	130	150	150	96	101	ns
16	0–15	205	350	295	274	166	147	80.52
	15–30	155	255	234	216	133	136	50.51
18	0–15	210	285	332	281	133	177	60.69
	15–30	165	230	214	218	112	126	61.20

Figures are means of four replicates.

ns: not significant.

After Khalid *et al.* (2000).

^aC/R: trunks and other palm parts removed from plots; C/S: trunks and fronds shredded on to plots; C/P: pulverised and shredded; P/B: chipped and burned.

bunch ash was used as a fertiliser. Their use as a form of compost for mulching the ground under oil palms is now much more likely, as this saves their nitrogen content, increases soil organic matter, improves soil structure and reduces erosion (Plate IVD). On average, for every tonne of FFB processed, 220 kg of EFB is produced. The fruit bunches are rich in potassium, but some of this is lost in the mill effluent (Table 11.29) during the processing. The typical content is shown in Table 11.26 (Gurmit *et al.*, 1999b).

The benefits of mulching with a nutrient-containing organic material are well known to gardeners. There is usually a yield response when EFB mulch is compared with normal estate fertilisers alone (Gurmit *et al.*, 1999b), with a range from 50 to 7% on inland soils, and a rather smaller mean response, from +36 to –6, on coastal soils. The best responses on these latter soils are on the riverine alluvium, whereas the responses are small on the more fertile marine alluvium. Unfortunately, it is sometimes unclear whether the comparison is made with equal total amounts of applied nutrients in all treatments, which is necessary for a proper comparison. The

Table 11.26 Composition of empty fruit bunches

Parameter	Dry matter basis		Fresh wt basis ^a (mean)
	Range	Mean	
Ash (%)	4.8–8.7	6.3	2.52
Oil (%)	8.1–9.4	8.9	3.56
C (%)	42.0–43.0	42.8	17.12
N (%)	0.65–0.94	0.80	0.32
P ₂ O ₅ (%)	0.18–0.27	0.22	0.09
K ₂ O (%)	2.0–3.9	2.90	1.16
MgO (%)	0.25–0.40	0.30	0.12
CaO (%)	0.15–0.48	0.25	0.10
B (mg/kg)	9–11	10	4
Cu (mg/kg)	22–25	23	9
Zn (mg/kg)	49–55	51	20
Fe (mg/kg)	310–595	473	189
Mn (mg/kg)	26–71	48	19
C/N ratio	45–64	54	54

^aMoisture content 60–65%.

After Gurmit *et al.* (1999b).

Table 11.27 Effect of EFB mulching on soil chemical properties on Lunas series

EFB mulched interrows									Unmulched Interrows							
Depth (cm)	pH	Organic matter		Acid fluoride-P (mg/l)	Exchangeable cations (meq./100 g)			6 N HCl extractable K (meq./100 g)	pH	Organic matter		Acid fluoride-P (mg/l)	Exchangeable cations (meq./100 g)			6 N HCl extractable K (meq./100 g)
		(%)			K	Mg	Ca			(%)			K	Mg	Ca	
		N	C				N	C								
0–15	5.5	0.26	3.66	42	0.88	1.22	0.83	1.02	4.8	0.26	3.82	12	0.07	0.04	0.21	0.15
15–30	5.7	0.15	2.77	11	0.99	0.20	0.22	1.23	4.9	0.14	2.39	6	0.09	0.03	0.08	0.16
30–60	5.6	0.09	1.22	9	0.47	0.06	0.09	0.64	4.8	0.08	1.37	11	0.05	0.03	0.09	0.24
60–90	5.4	0.05	0.63	14	0.32	0.04	0.08	0.45	4.9	0.04	0.81	19	0.06	0.02	0.08	0.35

After Gurmit Singh *et al.* (1999b).

soil benefits from EFB are as expected from its composition, with increases in pH, exchangeable cations, available phosphorus in the topsoil and soil structure. The increases in organic carbon and nitrogen are small and irregular (Table 11.27) (Gurmit *et al.*, 1999b). The usual experience is that a continued programme of organic material addition is necessary to increase soil carbon and nitrogen significantly, and it is not surprising that a single addition, in tropical conditions, has little effect. Assuming 220 kg EFB/t FFB, moisture content 65% and 2.8% K in the dry EFB (Gurmit *et al.*, 1999b), this amount would supply about 2.1 kg K. If one assumes a 25 t/ha yield of FFB, over 52 kg of K would be in the EFB produced from 1 ha. The FFB normally contain about 0.67% K and about 55% dry matter (Ng and Thamboo, 1967), so 25 t FFB would contain a little less than 100 kg K (Section 11.1.3). The EFB thus carries nearly half of the K originally in the FFB, and its recycling is essential for an efficient plantation. The only argument against this is the trouble and expense of transporting EFB from the factory to the fields, particularly the distant ones (Plates VD, E). If the transport system is under pressure, the movement of EFB will always have a lower priority than that of FFB, but it is an essential task.

The C/N ratio of EFB is large, with a mean of 54. Microbial breakdown, initially by fungi, is therefore rather slow, and the bunches take 6–8 weeks before they start to disintegrate. The biological process is complicated (Thambirajah *et al.*, 1995), and if the C/N ratio is sufficiently reduced by loss of carbon dioxide over time or by adding nitrogen and possibly phosphorus, the fungus disappears and the further process depends on bacteria. Sunitha and Varghese (1999) tested five methods of composting EFB to improve recycling of nutrients. The release of K is very rapid, but no N release occurred in the field during a period of

Table 11.28 Chemical characteristics of palm oil mill effluent (POME)

pH	4.7	Phosphorus	18
Oil and grease	4,000	Potassium	2,270
Biochemical oxygen demand	25,000	Magnesium	615
Chemical oxygen demand	50,000	Calcium	439
Total solid	40,500	Boron	7.6
Suspended solid	18,000	Iron	46.5
Total volatile solid	34,000	Manganese	2.0
Ammoniacal nitrogen	35	Copper	0.89
Total nitrogen	750	Zinc	2.3

All parameters are in mg/l, except pH.
After Ma (1999a).

10 months. Loss of dry matter was exponential, with 50% loss after 3 months (Lim and Zaharah, 2000) (Section 10.1.3.2).

11.7.2.2 Use of palm oil mill effluent

A palm oil mill generates about 0.67 t of liquid waste for each tonne of FFB processed, and in 1997 Malaysia produced about 32 million t of POME from 290 mills. This fluid has a high biological oxygen demand (BOD), and is stated to be 100 times more polluting than ordinary raw domestic sewage (Ma, 1999a, b). There are various fractions of POME (Table 11.28) (Lim K.H. *et al.*, 1999), arising from differences in treatments (Ma, 1999a, b). This section considers only the nutritional implications of recycling, but spreading on land also forms an efficient method of disposal, and the environmental implications are usually considered to be more important than the nutrient content. Current methods of treatment and application (Lim K.H. *et al.*, 1999) are accepted as not causing damage to the environment. The average composition of POME (Table 11.29) (Ma, 1999a, b) shows the huge oxygen demand and the useful amounts of nutrient. Again assuming a 25 t yield of FFB, this produces 16.75 t

Table 11.29 Chemical values (mg/l) for digested palm oil mill effluent (POME) and nearby groundwater and streamwater above, at and below the mill site

Chemical parameter	Digested POME	Groundwater	Streamwater		
			Before site	At site	After site
N	195 (25–476)	4 (0–10)	3 (0–10)	3 (0–14)	3 (0–11)
P	14 (0–130)	0 (0)	0 (0)	0 (0)	0 (0)
K	966 (122–2, 031)	7 (0–56)	3 (0–22)	2 (0–13)	1 (0–6)
Ca	149 (13–1, 288)	5 (0–20)	4 (0–16)	7 (0–25)	5 (0–34)
Mg	236 (124–545)	3 (0–11)	2 (0–13)	2 (0–6)	3 (0–11)
Mn	1.21 (0–20.13)	0 (0)	0 (0)	0 (0)	0 (0)
Fe	6.51 (0–58.75)	3.30 (0–32.50)	0.32 (0–1.13)	0.49 (0–1.38)	1.38 (0–9.75)
Cu	0.06 (0–0.60)	0 (0)	0 (0)	0 (0–0.03)	0 (0)
Zn	0.57 (0.07–7.55)	0.10 (0–0.65)	0.01 (0–0.06)	0.02 (0–0.08)	0.060 (0–0.30)
Pb	0.04 (0–0.75)	0 (0)	0 (0)	0 (0)	0 (0)
Cd	Trace	0 (0)	0 (0)	0 (0)	0 (0)
B	2.24 (0–16.50)	0 (0)	0 (0)	0 (0)	0 (0)
NH ₄	123.3 (3.50–227.5)	3.49 (0.70–20.30)	2.84 (0.70–4.90)	2.56 (0–6.30)	2.75 (0.35–5.60)
NO ₃	96.1 (5–520)	7.55 (0–47.50)	4.41 (0–69.00)	2.17 (0–25.60)	3.62 (0–19.80)
pH	7.40 (5.20–8.50)	5.39 (3.65–6.45)	5.60 (4.10–8.00)	5.73 (4.80–7.60)	5.53 (4.93–7.65)

Data are mean values (ranges).

After Lim K.H. *et al.* (1999).

of POME containing over 20 kg of total nitrogen, of which about 1 kg is ammonia. The other nutrients are 0.5 kg P, 60 kg K and 16 kg Mg. These numbers are clearly very variable, but this suggests that POME and EFB together contain virtually the same potassium as that in the FFB, as is expected if there are no other losses.

The combined use of POME and EFB thus replaces much of the lost nutrient. POME can be applied to land in Malaysia if the BOD is below 5000 mg/l. The most difficult aspect is the expense of distributing POME for application at some distance from the oil mill. The liquid is applied to various structures that confine it and allow it to percolate into the soil, such as longbeds and flatbeds (Lim, 1988; Lim K.H. *et al.*, 1999) (Fig. 11.22) (Plate IVB). These are costly to build and operate, and are usually not sited further than 3 km from the mill, because of the cost of piping. Alternatively, the POME can be spread by a sprinkler, fed from piping or carted by road tanker. For this reason the POME is not applied uniformly to different fields, and some fields possibly receive more nutrient than the palms can absorb. This is probably the greatest barrier to efficient recycling of nutrients in appropriate amounts to each field.

Lim (1988) applied 'ditch supernatant' POME to flatbeds under palms at five rates up to 10 cm rainwater equivalent (i.e. depth on the land surface); the flatbeds occupied one-sixth of the total area, so the depth applied in the flatbeds was up to 120 cm. The results

were favourable, but at the upper levels calcium and magnesium filled the exchange complex, to the point where they could interfere with the uptake of potassium. There is a possible link with the reported effects on high-calcium volcanic soils (Section 11.4.6). pH was raised sharply up to a maximum of 7, but the soil effects did not to spread beyond 80 cm downwards and 100 cm laterally with 10 cm equivalent of POME, and only a very little farther with 20 cm, on Serdang series soil. The standard amount per year was taken to be 10 cm, and applied at intervals of 2 months gave a yield increase of 20%, whereas 20 cm depressed yields, probably because it produced anaerobic conditions in the soil. The increase was attributed to both the nutrients and the additional water supplied to the palms.

When similar quantities per unit area of tank-digested effluent were applied by sprinkler, the effects could not be detected farther down than 30 cm, and there was no sign of suppression of potassium uptake. All effluent rates produced higher FFB yields than the control, which received the normal fertiliser treatments. POME applied with a sprinkler killed soft weeds, which regenerated after 2–3 months. If the objective is to return nutrients to the plantation, the sprinkler system will produce more uniformly favourable conditions in the soil, although there are practical problems with blocked nozzles.

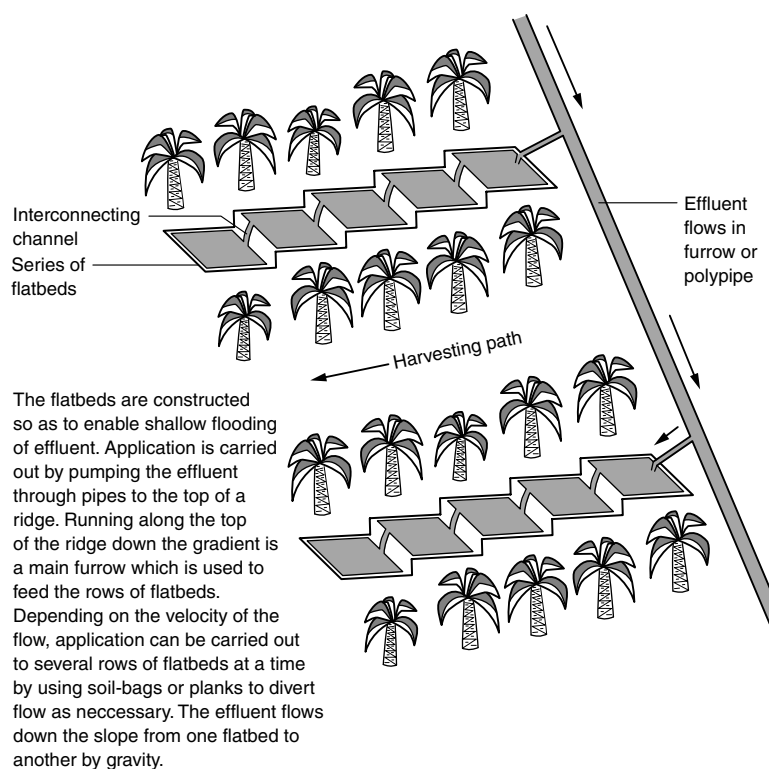


Fig. 11.22 Flatbeds for flooding and infiltration of POME, with gravity flow from one level to another. (After Lim K.H. *et al.*, 1999.)

There have been many questions about whether POME applications damage the quality of surface and groundwater nearby (Lim K.H. *et al.*, 1999). The effects are minimal with the usual rates of application, and it is almost certain that environmental damage is very rare (Table 11.29). Hamdan *et al.* (2001) monitored water quality in streams and wells, and found no contamination of water by heavy metals or other chemicals.

New methods of dealing with POME and EFB together (Section 10.1.3.2) may simplify the handling of wastes and the uniform return of nutrients to the whole estate.

11.7.3 Consequences of removal of biomass

Until recently, it was taken for granted that organic refuse from fronds and trunks would be left on the field (see Section 10.1.3.2). Refuse is now described as biomass, which can be used for pulp, paper (H. Kamarudin *et al.*, 1999), various forms of building board or even furniture (Koh *et al.*, 1999). Surprisingly, the trunks, fronds, palm press fibre, EFB and POME can also be used in animal feed (Abu Hassan and Yeong,

1999), in addition to the well-known palm kernel cake (Section 13.6.).

The nutrients in these various residues are already being recycled to the palm fields, or will be recycled as plantations become more efficient. Any removal of wastes and residues may therefore change the nutrient balance, and nutrient loss for this reason must be calculated and replaced in fertilisers. It will also be necessary to monitor carefully the organic carbon and nitrogen in the soil, as well as its structural properties, to ensure that the general properties of the soil are not being damaged by such removals; this seems unlikely, as most of the residues may decay and be mineralised to carbon dioxide on the soil surface.

11.7.4 Loss mechanisms of nutrients

11.7.4.1 Water-based mechanisms

The subject of the preceding sections was how to return nutrients in a plantation so as to close the nutrient cycles as far as possible (Section 11.7.3). In other loss mechanisms recycling is irrelevant, and the losses need to be reduced directly. These are erosion, by which chemically fertile topsoil is carried away; runoff,

by which applied fertiliser is carried away in surface water during heavy storms; and leaching, in which nutrients are moved down the profile until they reach a water table or a depth where there are no palm roots. All of these mechanisms are site and time specific.

Leaching is difficult to measure because it requires measurements of the concentration of the soil solution, and of the amount of water moving down the profile. Both of these vary with time because of the weather alterations, and with depth because of reactions in the soil, and the uptake of water and nutrients by roots. Measurement is particularly difficult with oil palms because the incident rainfall varies sharply with position, owing to the effects of the canopy, and the infiltration of water into the soil varies where the soil has been compacted in harvesting paths. However, the latest review of the subject (Henson, 1999c) suggests that losses to leaching are fairly small, at 6–11% of applied nutrients. Nitrogen and potassium are the elements most at risk, because of rather weak adsorption of ammonium and potassium ions, and nil adsorption for nitrate. Chang and Zakaria Abas (1986) used catchment studies to show that only 2 kg N and 8 kg K/ha per year were lost from a young palm field. Foong (1993) found that fertiliser losses in a lysimeter decreased sharply with palm age, from 17% for N, 1.8% for P, 10% for K and 70% for Mg at 1–4 years, to 2.1% for N, 1.5% for P, 2.7% for K and 13.5 % for Mg at 5–14 years (Table 11.19). The most surprising result was the large loss of magnesium, but this is probably due to the less rapid plant uptake of this ion than of potassium, and the weaker adsorption on the exchange complex than for calcium. The leaching losses were much higher at the early stage, presumably because of the small plant uptake. However, these data are so dependent on the rate of fertiliser in relation to the rate of palm uptake, and other site-specific factors in the lysimeter such as the necessarily artificial water relations there, that it is difficult to accept such results as generally applicable. More studies are badly needed. The very heavy fertiliser rates per unit area that are found within the palm circle, if all fertilisers are applied there, must encourage leaching owing to the high concentration of soluble ions near to the stemflow of water from the trunk. The difficulties of practical work in this subject suggest that some of the new mathematical models for leaching in other crops should be applied to oil palms (Tinker and Nye, 2000).

Runoff and erosion are negligible in most tropical soils that are protected by a forest canopy (Sanchez, 1976, p. 362), but can be extreme on cleared unprotected soil, especially if on a steep slope. The opening up and land preparation stages are thus vulnerable (see Section 8.3.1). Under complete canopies one would not expect serious

losses unless the slope was steep. Runoff losses occur almost entirely soon after fertiliser has been added, and so depend very much on management in relation to rainfall. Teoh and Chew (1985) argued that frequent applications during the year were unnecessary and could be damaging, if applications therefore fell in a rainy period. They found that application in the driest period in Malaysia was best, as total rainfall was low, and there was a soil water deficit. The last factor is important, because it means that all nutrients dissolved in a shower of rain enter the soil at once. Kee and Chew (1996) made three erosion plot studies in Selangor, Kelantan and Sabah, all with different soil types, with rainfalls from almost 2000 to 2700 mm and slopes of 5–7°. Runoff losses were very small except after a combination of a recent fertiliser application and a heavy rainfall, when concentrations of up to 130 ppm N were found in the surface water. If the rainfall following an application was light, the water did not run off, and losses from that application were then very small.

Erosion losses were also measured on the same sites. Soil losses were always less than 9 t/ha, which is regarded as acceptable, although a lower limit of 2 t/ha is used in many other parts of the world. Whereas the main losses of the most soluble fertilisers, nitrogen and potassium, were via runoff, the main loss of phosphate occurred during soil erosion, as would be expected. Pruned fronds stacked along the contour had no effect on runoff, but reduced soil erosion significantly. Overall results on the Selangor soil are shown in Table 11.30 (Kee and Chew, 1996); these phosphorus losses were mostly under 10% of applications. The average runoff of water was 23–28% of rainfall on these three sites. This is much larger than the percentage loss of nutrient, so many rainfall episodes must have had very little effect on nutrient loss, because there was no fresh fertiliser lying on the surface. These losses are smaller than those found by Maene *et al.* (1979) on Durian series, except for loss of potassium, which was larger on the Selangor soil. Erosion losses from palm avenues were greatly reduced by EFB mulching, from 27 to 2.3 kg soil, and the savings of phosphate would have been proportionate (Gurmit *et al.*, 1999b).

The conclusion is that water-related losses are smaller than was thought at one time, but they are by no means trivial and must be reduced as far as possible. Unfortunately, there is no overall solution, and success will depend on the careful work of agronomists and managers on the spot.

11.7.4.2 Atmospheric losses

The most important effect is the loss of ammonia by volatilisation from urea. Almost certainly there are also

Table 11.30 Summary of net nutrient losses (1992–1994) in an oil palm ecosystem by surface runoff and eroded sediments

Nutrient	Net annual losses in runoff (kg/ha per year)	Net annual losses in eroded sediment (kg/ha per year)	Net total losses (kg/ha per year)	Net nutrient loss as % of nutrient applied at rate 1 ^a
N	4.5–7.2	0.5–0.8	5–8	5–8
P	0.7–1.1	0.5–1.3	1.2–2.4	0.8–1.6
K	20.8–33.0	Trace	21–33	9.8–15.3
Mg	3.6–6.8	0.1	3.7–6.9	4.1–7.6

^aMean (1992–1994) fertiliser input at rate 1 was equivalent to: 101 kg N, 145 kg P, 215 kg K and 90 kg Mg/ha per year.

After Kee and Chew (1996).

significant losses into the atmosphere as N_2 and N_2O after anaerobic denitrification in waterlogged soils with large supplies of organic carbon (Aulakh *et al.*, 1992), such as occur in some coastal plantation soils with high water tables. However, no work appears to have been done on this. Nitrous oxide is fairly stable in the atmosphere, and acts as an important greenhouse gas (IPCC, 2001), so this is an environmental issue. Despite its environmental importance, the measurement of nitrous oxide evolution is very difficult, because of both spatial and temporal variation. This variability seems to be an unavoidable part of the denitrification process in the field (Christensen and Tiedje, 1988), explaining why data for rate of production have extremely high errors. These atmospheric losses have the additional problem that ammonia becomes oxidised to nitric acid in the atmosphere, and so can contribute to acid rain. For example, agricultural ammonia loss is now the largest cause of acid rain in the UK.

Losses of ammonia from urea are difficult to quantify, as they depend on the moisture present, the temperature and the degree to which urea granules stick to leaves. The greater part of the loss occurred in the first 3 days after application (Chan and Chew, 1984; Chew *et al.*, 1992) (Table 11.18), and the losses were surprisingly constant at around 30–40% of that applied, the proportion being only slightly larger at a rate of 500 kg N/ha than at 250 kg N/ha. Hussin (1995) found some losses as high as 50%, and considered the losses to be due to the formation of alkaline microsites around the granules. If the urea was mixed with acidified POME to absorb the ammonia, this loss was reduced from an average of 30% to 8%. With such large and varying losses it is difficult to know how it is possible for estates to fertilise accurately.

Chew *et al.* (1992) summarised how losses could be diminished. The losses will be less if the vegetation is dry, so that granules fall down onto the soil, and if light

rainfall very soon afterwards washes the urea into the soil. If this is, as usual, acid, then the urea, and later the ammonia, will be quite strongly held. The urease enzyme that catalyses the transformation of urea to ammonium carbonate, which then splits to ammonia plus carbon dioxide, is very widespread in the environment, so the possibility of losses is always there. Losses will also occur from applied ammonium carbonate because carbonic acid is such a weak acid, but not to any extent with calcium nitrate or ammonium sulfate or chloride. This is a loss of an expensive input, although urea is usually the cheapest of the nitrogen fertilisers. More worrying is that the manager has lost control over the rate of nitrogen fertiliser that is being used, and that there is a temptation to apply a large excess to compensate for the losses ‘for safety’, and so unbalance the fertiliser applied.

11.7.5 Soil changes during the life of a plantation

There was at one time considerable interest in the possibility of soil changes during the life of a plantation (Hartley, 1988, p. 522). In modern terminology, this is a question of agricultural and soil sustainability (Chan, 2000a). Kowal and Tinker (1959) studied this in Nigeria, where fertilisers would not be used by the local farmers. In effect, it was posing an analogous question to that during replanting now: if the plantation was opened from forest, what fraction of the nutrients in the forest was absorbed by the palms, and for how long would this suffice? It was found that soil nitrogen and organic matter changed very little with time; interpreted in current terminology, this means that the organic matter level that was in near equilibrium with forest was also in near equilibrium with oil palms. The soil structure remained good as long as there was a reasonable cover. This is excellent evidence for the similarity of the two ecosystems and the

sustainability of oil palm plantations. The only other change was that the three major cations decreased over the next 15 years, potassium rapidly, but calcium and magnesium slowly. This clearly represents the offtake of K in FFB and the growth of the palms. The input of exchangeable potassium from felling the forest was estimated at 450 kg/ha (Tinker, 1959). The loss of exchangeable potassium from the top 3 m of soil from 5 to 20 years of age was 360 kg K/ha, while the total net uptake was estimated as 670 kg/ha. The origin of the difference was not clear, but could have been from non-exchangeable potassium sources, or from potassium held exchangeably at greater depths. In brief, the only significant change with age on these soils was a major depletion of potassium. Under present conditions this decline would be met by the application of fertilisers, giving a stable palm ecosystem up to at least the age of 20 years. So long as the organic matter and total nitrogen levels can be held stable, and the physical characteristics maintained, there is no obvious reason why oil palm cropping should not continue indefinitely.

Yeboua and Ballo (2000) studied long-term changes in a soil in the Ivory Coast intended for replanting. The clay content of the plantation topsoil was 35% less than that in the equivalent soil under forest. The authors suggested that deflocculation of clay had occurred and that it had been removed in surface wash, or moved down the profile to the subsoil, but such a massive effect seems rather unlikely, and should be easily visible in a soil profile. The pH remained the same, but the 'aluminium toxicity risk' was four times higher under palms. This could be associated with the observed decrease in organic matter. Phosphorus, nitrogen and cation levels also decreased. This suggests that oil palms alone are not a long-term protective crop, but there must be some doubt about whether the comparison with original forest was reliable in this work. The effects are far larger than those reported elsewhere. Erhabor and Filson (1999) tested combinations of crops and oil palm. They found no change in soil pH, but some surprisingly large and inconsistent changes in soil components such as soil organic matter. It is questionable whether all field research is carried out under reasonable field conditions.

11.8 DEFICIENCIES AND TOXICITIES IN SPECIAL AND UNUSUAL SOILS

11.8.1 Acid sulfate soils

Normally, the only problem with these soils for oil palms is their extreme acidity, which prevents root development

(see Section 3.4.3.3) (Dent, 1992; Tayeb Dolmat, 2000). The danger to the palms is a combined toxicity of aluminium, iron and manganese. Trivalent aluminium is already present in the soil solution at pH 4, where palms can grow well, so simple aluminium toxicity is not likely. However, the concentration of Al^{3+} is many times larger at pH 3 (Sanchez, 1976), and may well exceed the palms' acceptable limits. No work appears to have been done on this subject. Since the living roots of the palm should not be in the acid layer, no action is necessary.

11.8.2 Volcanic soils

Some volcanic soils in Sumatra give unusual results for potassium uptake (Foster and Prabowo, 1996b) (Section 11.4.6). Five field experiments were done there, and on the one sedimentary soil normal results for potassium were found. On volcanic soils rachis potassium concentration (Section 11.4.2.2) was better correlated with response to potassium than was leaf potassium. This was largely because there was an unusually low critical level for leaf potassium. The rachis potassium concentration correlated with soil HCl-extractable potassium, but not with exchangeable potassium. It was necessary to balance potassium against other cations (calcium and magnesium) to explain the system. Elsewhere (Ollagnier *et al.*, 1988), the very low leaf critical potassium level of 0.5% in Sumatra has been explained by the water supply, although this is not very convincing. Foster and Prabowo (1996b) suggested that the leaf critical levels for potassium on volcanic soils in Sumatra are so different to those on all sedimentary soils because of their clay minerals. These soils, and the coastal clay soils in Malaysia where the potassium critical levels are also low, have 2:1 layer clay minerals and amorphous silicates (allophanes), respectively, whereas almost all other oil palm soils have kaolinitic 1:1 clay minerals. This changes the K/Ca exchange relationship, lowers the activity ratio $\sqrt{K/(Ca + Mg)}$ and decreases the availability of potassium. The theory is interesting but needs further research.

There has been a continuing debate about the place of chlorine in palm plant nutrition, (Section 11.4.5) and relevant effects have appeared on volcanic soils. Foster *et al.* (1993) conducted a series of experiments on alluvial volcanic soils in PNG. The chloride contents of the soils and palms were very low, despite being not far from the sea. Potassium chloride increased the moisture content of the palm tissues. Again, rachis potassium was better related to the addition of potassium, and to the yield response to potassium, than was leaf potassium. In practice, this makes little difference to the practical value of the soils, and a full explanation will have to

await a better understanding of the ion and water control systems of the palm, and how they interact with the composition of the soil solution.

11.8.3 Coastal alluvial soils

The most striking characteristic in Malaysia is the considerable availability of potassium, and the large content of non-exchangeable potassium. Despite this, the critical potassium level in the leaves of palms grown on these alluvial soils (Selangor or Biah series) is below that found on the inland soils such as Rengam, which seems to be a less extreme case of the situation on volcanic soils. A much better understanding of the soil chemistry controlling release of K is needed.

11.8.4 Peat soils

These have been discussed earlier (see Sections 3.4.3.7 and 8.3.6). The manuring treatments needed have been studied more intensively, as they have been taken into use for oil palms. Tayeb Dolmat *et al.* (1996) state that 'Peat has a very inadequate and unbalanced nutrient status'. This varies with the peat origin (see Section 3.4.3.7), but in general its nutrient behaviour is indeed very different from that of mineral soils, not only because of the lower quantities of nutrients that may be present, but also because their chemistry is very different. If the peat starts with a very high C/N ratio, the supply of mineral nitrogen will be inadequate. Gradually, the carbon is lost by oxidation after drainage of the peat, and the new and lower C/N ratio slowly increases the supply of mineral nitrogen. A trial with fertiliser and palm density treatments on deep peat (Table 11.31) (Tayeb Dolmat *et al.*, 1996) showed that potassium gave marked yield

responses, especially later at the lower planting densities. As fertiliser was added on a per palm basis, the amount of fertiliser added per hectare was larger at the higher densities so comparisons were difficult. Potassium is held very loosely by the wholly organic exchange complex, in comparison with the divalent ions calcium and magnesium, and there are no minerals containing non-exchangeable potassium. It is therefore normally necessary to supply a substantial rate of fertiliser potassium.

A high C/N ratio implies a high C/P ratio also. However, there is no strong adsorption mechanism for phosphate ions as in mineral soils, so phosphate present is highly available, but more easily leached out. Phosphate fertilising is therefore usually important. With the high yields obtainable on deep peats, of up to 30 t FFB/ha, it is essential to follow the nutrient balance carefully. All the three major nutrients have an effect on basal stem rot (*Ganoderma*) on peat, with nitrogen and phosphorus increasing its incidence and potassium decreasing it (Tayeb Dolmat and Hamdan, 1999) (see Section 12.1.6.3). Gurmit (1990) found conflicting results of potassium chloride and urea on coastal soils. Finally, the micronutrients copper and zinc are so important they should be applied if there is any suggestion of a deficiency by either visual symptoms or leaf analysis (Gurmit, 1988). It may be advisable to use a light dressing of limestone to control the pH if this is very low.

11.8.5 Trace element deficiencies and toxicities

Poeloengan (1995) reported that some ultra-basic igneous rocks containing serpentine produced soils on weathering that were low in calcium, but high in

Table 11.31 The effects of potassium fertilisers on oil palms planted on deep peat

Year of harvest	D1 (120 palms/ha) FFB yield (t/ha per year)			D2 (160 palms/ha) FFB yield (t/ha per year)			D3 (200 palms/ha) FFB yield (t/ha per year)		
	K ₁	K ₂	K ₃	K ₁	K ₂	K ₃	K ₁	K ₂	K ₃
1	12.5	12.9	13.2	17.5	17.0	17.1	12.1	20.0	21.3
2	15.4	15.5	15.6	20.1	19.9	19.7	23.4	23.1	25.1
3	18.1	18.5	19.7	25.0	24.7	26.0	26.9	28.3	30.3
4	23.1	23.0	24.1	30.1	29.9	30.0	31.8	32.4	33.8
5	23.8	25.1	26.1	27.4	29.1	29.5	30.6	29.8	29.2
6	22.5	24.5	26.2	26.7	27.2	28.1	27.7	27.9	27.6
7	21.1	23.4	26.5	25.3	27.4	26.2	28.5	27.6	30.3

K₁: 3.2 kg, K₂: 6.4 kg, K₃: 9.6 kg bunch ash/palm per year. D = planting density.
After Tayeb Dolmat *et al.* (1996).

iron and magnesium. They also contain of the order of 5000–6000 ppm of nickel. This causes a severe toxicity in oil palms, with leaf symptoms resembling those of iron deficiency when the content of leaf 17 is above 20 ppm Ni. In very severe cases no fruit is produced.

On a very sandy Tertiary sedimentary soil in Brazil, Pacheco *et al.* (1986) reported finding copper deficiency in a nursery, with concentrations of only 2 ppm in the leaves, which showed marked deficiency symptoms. The critical level was assessed as 4.5 ppm. Wanasuria and Gales (1990) also found copper deficiency in very sandy mineral soils in Indonesia. It is well known that copper deficiency is found in peat soils, but in mineral soils it can also be caused by extremely small total concentrations. In this case the total copper was only 1.6 ppm. There was a suggestion that zinc deficiency was also involved, but the total concentration for this element was probably sufficient at about 6 ppm. High rates of phosphorus and nitrogen fertiliser increased the deficiency symptoms, probably by increasing the plant demand.

Copper and zinc are deficient on peat soil because these elements are strongly complexed by soil organic matter, both soluble (fulvic) and insoluble (humic) organic compounds with multiple carboxyl and hydroxyl groups. Gurmit (1988) reported that a previously identified disease, 'peat yellows', was in fact zinc deficiency. It is notable that although zinc deficiency symptoms had been produced in sand culture many years before (Bull, 1961b), this did not allow a clear identification of the disease when seen in the field. The disease can be cured or prevented by spraying with zinc salts or by applying zinc salts to the peat before planting. The deficiency is more apparent on replanted areas, and both soil and foliar applications are then recommended. Yields responses varied from 12 to 78%.

Not surprisingly, micronutrient deficiencies have been found in seedlings grown on peat soil in pots. In Sumatra, Sidhu *et al.* (2001) found clear copper deficiency and possible iron deficiency in pot-grown palms, with 40% of a large nursery being stunted. Symptoms were as described in Section 11.4.1. A fast response was possible with foliar sprays, but soil applications also produced healthy plants, with full recovery of seriously affected seedlings. For iron, cure was only partial, as is to be expected with an element that is non-mobile and depends on the transpiration stream for its translocation to the shoot.

The great majority of the world's oil palms grow on acid soils, often in the pH 4–5 range. Because of the low solubility products of their hydroxides, the availability of most of the trace metals increases with decreasing pH, as the metallic cations remain in an acidic soil solution. This is particularly marked with iron and manganese, partly

because of their variable valency. It is therefore intrinsically unlikely that iron and manganese deficiencies would be found in the field except in rare oil palm soils with pH above 6. However, there are some soils with very low total manganese concentrations of less than 20 ppm, and manganese deficiency was found in palms on a sandy colluvium derived from Rengam series soil (Kee *et al.*, 1995a, b). Soil and foliar treatments were effective, and 25 ppm Mn in leaf 17 was the critical level for the deficiency. The symptoms were interveinal chlorosis with a distinctive appearance of white stripes across the leaf.

Boron deficiency is widespread, often occurring briefly and then disappearing. Hartley (1988) calls it 'the most elusive of the deficiencies of the oil palm'. The symptoms, especially little leaf, have been noticed for many years, and reproduced in sand culture (Bull, 1961b; Bull and Robertson, 1959) (Section 11.4.1.3). Symptoms and corrective procedures have most recently been described by Corrado *et al.* (1992). Boron deficiency usually appears on sandy soils, and in other crops it is most frequent on neutral or alkaline soils. In oil palms it has been difficult to associate it with particular soil types.

11.9 PRACTICAL MANAGEMENT OF FERTILISERS

11.9.1 Planting density and palm age

It is well known that the planting density of palms affects their response to fertilisers (Hartley, 1988, p. 556). In general, responses are larger at the lower density of planting, and may be quite absent at higher densities (but see Table 11.31). This occurs with constant fertiliser rates per hectare. A general response to fertiliser is to produce larger crowns with a higher leaf area index. This may produce conditions where more vegetative dry matter is produced and lead to increased interpalms competition at high palm densities. The basic question is not how much response there is to fertiliser at different densities, but what condition produces the highest yield for the lowest cost. Yield per unit area plotted against plant density usually produces a curve with a long plateau (see Section 4.3.1), and fertiliser responses can raise this plateau. In the absence of direct field evidence, the best solution is therefore to aim for a density that is at the lower end of the plateau, and then to apply fertiliser (Goh, 1982).

The age of palms is important in two respects. First, there may be differences in the fertiliser requirement. Secondly, leaf analysis results may be different at different ages of palms grown on the same soil, particularly for nitrogen and potassium (Section 11.4.4.2).

Foster and Chang (1977) found that the concentration of nitrogen, phosphorus, magnesium and calcium, but not potassium, in leaves declined with palm age, whereas others also found marked declines in potassium. It is possible that such a decline may be due to inadequate annual applications of potassium, so that the lower leaf concentration correctly indicates a growing deficiency (Hartley, 1988). The inconsistency of the results on this topic suggests that there may be some artefacts, or that soil type has a large effect.

11.9.2 Fertiliser materials

11.9.2.1 General

The oil palm industry uses about 50% of the total fertiliser consumption in Malaysia (Chew *et al.*, 1992), although these authors believe that this is an

underestimate. Expenditure in 1992 was US\$150/ha, or over \$305 million in total. Mutert and Fairhurst (1996) stressed the large fraction of fertiliser imports, some 16%, now used by the oil palm industry in all of South-east Asia. If capital costs are excluded, it has been estimated (Tan, 1988) that 36% of the total cost of producing oil palm products arises from the use of fertiliser. With the recent spell of lower prices for palm oil, the cost of fertilisers has become a major issue in efficient production. In these circumstances some estates are believed to cut the application rates sharply, but this is a short-term and rather desperate temporary expedient.

The fertiliser materials usually used in the oil palm industry, with their content of nutrient elements and methods of application, are discussed by Tang *et al.* (1999), Chew *et al.* (1992) and Teo *et al.* (1998), and are set out in more practical detail by Rankine and Fairhurst (1998c, d) (Table 11.32). Goh *et al.* (2000)

Table 11.32 Commonly used fertilisers for oil palms. Note use of oxide formula still in use.

Nutrient source	Main nutrients	Nutrient content (%)								
		N	P ₂ O ₅	K ₂ O	MgO	CaO	B	Cu	S	Cl
Straight fertilisers										
Urea	N	46								
Ammonium nitrate	N	35								
Sulfate ammonia	N, S	21							24	
Diammonium phosphate	N, P, S	18	46						11	
Rock phosphate	P, Ca		30			45				
Triple super phosphate	P, Ca		46			20				
Single super phosphate	P, Ca, S		18			25			11	
Muriate of potash (potassium chloride)	K, Cl			60						35
Sulfate of potash (potassium sulfate)	K, S			50					17	
Langbeinite (Mixell salt)	K, Mg, S			22	18				22	
Kieserite (magnesium sulfate)	Mg, S				27				23	
Dolomite (magnesium carbonate)	Mg, Ca				22	30				
Sulfur	S								97	
Sodium borate	B						11			
Copper sulfate (CuSO ₄ · H ₂ O)	Cu							25	13	
Compound fertilizers										
12-12-17-2	N, P, K, Mg	12	12	17	2					
15-15-6-4	N, P, K, Mg	15	15	6	4					
15-15-15	N, P, K	15	15	15						
Palm residues ^a (Section 11.7.2)										
Bunch ash	K, Mg, Ca		4	40	6	5				
EFB	N, K	<1	0.1	1.2	0.1	0.1				
Pruned fronds	N, P, K	0.5	0.1	0.8	0.1	0.2				
POME	N, K, Mg	0.4	0.2	1.3	0.4					

^aPalm residue nutrient contents are given on a fresh weight basis. Thus, 30 t EFB delivers about 100 kg N, 12 kg P, 300 kg K, 20 kg MgO and 21 kg Ca.

After Rankine and Fairhurst (1998c).

provided a good brief discussion of the factors that should control fertiliser policy in a plantation. A brief summary of the important points is given below.

11.9.2.2 Nitrogen

This causes practical problems, because of the complex chemistry of this element in both soil and plant. There are now over 20 models of the transformations of nitrogen in the soil (Tinker and Nye, 2000). The nutrient balance must take into account the amount brought in from the atmosphere in dry or wet deposition. This varies widely with position and geography, as the largest local sources are usually industrial, and a local source of information should be used if possible. The amount lost to the atmosphere from urea can be extremely large and depend on the short-term weather. Surface runoff can carry both newly applied fertiliser granules and enriched surface soil away, but low pH soils will tend to sorb and hold ammonia once it has entered the soil. Finally, there will be leaching of mineral nitrogen from the soil profile. All of these factors are difficult to determine in the field, and may vary widely over quite short distances (Section 11.7.4).

During the earlier years of the plantation, nitrogen will be fixed by the leguminous cover plants. The rate at which it is returned into the soil has been determined in specific situations, but it is difficult to extrapolate this widely. If the soil organic matter and organic nitrogen levels are slowly changing, some nitrogen is being released as mineral nitrogen, or bound into organic matter (Chew and Pushparajah, 1995). Careful soil analysis can determine this, but work of this sort is not justified or practical in all fields. In brief, nitrogen is a very difficult fertiliser to apply exactly in all agricultural systems, and the only approach is to apply the amount needed according to fertiliser experiments and leaf analysis. The growth and deficiency demands can be calculated, but the natural supply and loss will always be uncertain. The need for nitrogen is so important and so difficult to optimise that the application of a small excess is justified, but the increased leaching risk needs care because of the environmental implications.

There is a question about when nitrogen can be considered to be leached. In deep soils the palm roots penetrate down several metres (Section 11.2.1), and technically nitrate has not leached out of the root zone until it has moved beyond the deepest roots. This may be one reason for the surprisingly small response of mature palms to nitrogen on the deep sedimentary soil of West Africa and elsewhere. Assuming that the field capacity of these soils is about 0.3 volume fraction, it appears that at least a whole year's rainfall may be required to

move nitrate beyond the root zone (Section 11.2.1.2), because water is extracted from the soil by the roots, so that the velocity of flow of leaching water is much greater at the surface than at depth. During that period nitrate has a very good chance of being absorbed because of its high diffusion coefficient and uptake rate.

Ammonium sulfate is the standard nitrogen fertiliser, although it tends to acidify the soil as the ammonium ion is oxidised to nitrate (Section 9.1.4.2). This is not usually sufficient to be a serious disadvantage unless continued for a long time at heavy rates (Pushparajah *et al.*, 1977). A single application reduced the surface soil pH from 4.23 to 3.37, although this increased later. It can, however, act as an antagonist to magnesium, and induce magnesium deficiency symptoms (Tinker and Smilde, 1963a).

Urea tends to hydrolyse to ammonium carbonate and then to ammonia, some of which is then lost in volatilisation (Fenn and Hossner, 1985). In comparisons with ammonium salts it therefore often shows a low efficiency, although there is no physiological reason why this should be so. However, urea has become relatively cheap as it has been manufactured with local gas supplies, and it has therefore been used extensively (Hartley, 1988; Zin *et al.*, 1990). Zin *et al.* (1990) tested urea, in two granule sizes, against ammonium sulfate in 18 fertiliser trials with three rates, spread widely within Malaysia. When applied in the weeded circle, both urea treatments were consistently inferior to ammonium sulfate at the same nitrogen rate. When broadcast over the entire area, all three materials were of comparable efficiency at low rates (0.5 kg N/palm per year), but at higher rates the standard urea with 2.9 mm granules was consistently inferior. The reason is not entirely clear, because the larger granule of 7 mm size (forestry grade urea) should produce a larger and more alkaline microsite. It is probably due to the smaller specific surface of the larger granule, giving more time for the dissolved urea to enter the soil, and to the greater weight of each granule, causing it to fall straight to the soil, instead of sticking on wet foliage.

Ammonium carbonate is also prone to ammonia volatilisation. Ammonium salts (nitrate, chloride or phosphate) do not volatilise, and are all soluble. Calcium nitrate is highly soluble.

11.9.2.3 Phosphate

This ion has a complex soil chemistry that still requires more research to understand it fully (Sanyal and de Datta, 1991), along with the way in which this could explain the range of availabilities of soil phosphate arising from repeated fertilisation (Barrow, 1983). Its strong bonding to most soils (excessively strong with andosols with

allophanic minerals) means that there will be very little leaching, assuming uniform broadcast application. Over a longer period of regular applications, which allows equilibrium to be established, the nutrient balance system should work well: the immediate problem is to determine whether extra phosphate is needed to correct an existing deficiency, or whether the soil level is so high that the application rate can be reduced. The aim is to reach an equilibrium input–output state as soon as possible. However, this state must be broken at some point when replanting takes place and the nutrient situation is completely altered (see Section 11.7), and soil analysis should be used in this situation.

A second issue is the use of ground rock phosphate. This has proved very effective for two reasons. First, the soils are acidic, and rock phosphates are usually dissolved fairly rapidly in soils with pH below 5.5. Secondly, the use on a perennial plant allows time for the plant to absorb phosphorus slowly. However, the frequent recommendation to fertilise heavily with phosphorus and magnesium to encourage a vigorous stand of cover crops assumes that rock phosphate can dissolve quite quickly. Foong and Syed Sofi (1995) tested dressings of ground rock phosphate at 1-, 2- and 4-year frequencies, with a constant annual rate of 0.78 kg/palm and later 1.50 kg/palm. The annual FFB yield with 1 year was largest (143 kg/palm), 2 years slightly less (139 kg/palm) and 4 years clearly less (126 kg/palm). The economic return was largest with the 2-year application. There is growing evidence that some plants, such as grain legumes like *Mucuna pruriens*, have special mechanisms that allow them to use rock phosphate effectively, and thereby enhance its availability to following crops (Vanlauwe *et al.*, 2000). As far as we know the legumes used for oil palm cover crops have not yet been tested for such effects. In general, the use of very large rates of rock phosphate early in the life of the plantation, so as to raise the phosphate status permanently (Hartley, 1988), appears sensible. A similar suggestion is now being made for some African arable soils with low phosphorus status. Such applications are more in the nature of capital investment than a running expense.

Other fertilisers are monocalcium and tricalcium phosphate (superphosphate), and various ammonium calcium mixed-salt phosphates. All are easily soluble and quick acting, and pose no problems except for the possibility of strong soil adsorption.

11.9.2.4 Potassium

Potassium chloride is the standard fertiliser, and normally the most expensive fertiliser applied. The nutrient

balance system should work well in this case, as the off-take of potassium can be calculated fairly exactly; there is no atmospheric input or loss and rather little leaching. The cation is held to the soil cation–exchange complex with medium to low strength, and if fertiliser is applied broadcast, as is now becoming the main method in the industry, there is no local concentration, and the assumption of low leaching on soils of medium texture given moderate N fertiliser is probably well based.

Some soils are special, in the sense that they either release potassium from their slowly soluble minerals such as feldspars, or sorb potassium into non-exchangeable forms on mixed layer 2:1 clays (illites). This sorption is slowly reversible, and its direction depends on the soil solution composition with which the mineral would be in equilibrium, and the actual mean soil solution concentration at that time. Heavy rates of potassium therefore risk increasing the sorption on soils with these clays. Clearly, the assumptions in the nutrient balance are not met with such soils, and experimentation is needed (Fallavier and Olivin, 1988) which, together with field experience, will allow the net effect of fertiliser to be determined.

11.9.2.5 Magnesium

This is less widely used than the ‘big three’. There is a choice of soluble fertilisers: kieserite (magnesium sulfate), impure salts such as sylvinite or low-solubility sources such as dolomite (magnesium calcium carbonate limestone) (Dubos *et al.*, 1999). The latter is a very good and cheap source on highly acidic soils.

11.9.2.6 Compound fertilisers

The use of single-nutrient fertilisers allows great flexibility in making up individual field applications, but this means that each material has to be applied separately. Physical mixtures will normally segregate, so that the percentage of different nutrients can fluctuate sharply in different batches that have been weighed out from the mixture. These are called blends, and in some countries local blending plants will produce blends of the right composition to order.

Compound fertilisers are granular materials made from individual fertilisers, in such a way that the composition of each granule is the same. They are often based upon two-nutrient materials, such as the ammonium phosphates. Rankine and Fairhurst (1998c) discussed the use of compounds briefly. They are convenient to use, as only a single material has to be handled. However, the range of compositions on the market is limited, so

that the amounts applied may not be exactly those that have been chosen. Compositions are indicated by numbers such as 10-10-15-5, which indicates that the material contains 10% by weight of N and P_2O_5 , and 15% of K_2 and 5% of MgO. It is usual for compound fertilisers to be more expensive than single fertilisers, for the same weights of nutrients, and they are less used than single nutrients. Adiwiganda (2002) has produced a complete scheme for the use of a series of eight compound fertilisers, the element ratios being dependent upon which of 15 soil families the palms grow on, and the quantity of the compound fertiliser being dependent upon the stage of maturity of the palms. It may be simple to apply this scheme, but the fertiliser needs will vary within the soil families, and the best nutrient ratios will vary with palm age and position, so it seems unlikely that using such a limited number of compounds is adequate.

11.9.3 Methods and times of application

The general question of how and where to apply the fertiliser has been touched on elsewhere (Section 11.5.1). Teoh and Chew (1985) considered methods of application, noting how little experimentation had been done on this. Two factorial trials were done with three rates of both nitrogen (ammonium nitrate) and potassium, with fertilisers applied once, twice or three times, and either broadcast or placed in the weeded circle. The conclusion was that there was no significant difference between fertiliser placed in the circle or broadcast, even though results for placement in the circle were always slightly larger, and the concentrations in the 17th leaf were also usually larger. There was a significant effect in favour of placement in one year in one trial. The placement of fertiliser is a well-known technique in many forms of agriculture, the general aim being to concentrate the nutrients in a favourable position, and in particular with soluble phosphates, to reduce the amount and effect of strong adsorption of phosphates (Sanchez and Uehara, 1980; Barber, 1995). Placement may be cheaper than broadcasting if done manually. If there is a benefit from placement, it probably results from the acidification of the soil under the weeded circle causing a more rapid dissolution of rock phosphate. However, Teoh and Chew (1985) point out that the dangers of runoff are greater with placement. Also manual placement carries the risk of careless or improper placement, or pilfering of fertiliser, that are less likely with mechanised broadcasting (Colman *et al.*, 2002b).

Knowing the density of the surface root system in mature palms (Section 11.2.1), it is difficult to believe

that soluble fertilisers such as nitrogen and potassium are not efficiently absorbed when broadcast. The incentive for broadcasting fertiliser now arises mainly from the labour shortage in Malaysia, which can be relieved by mechanised fertiliser spreading, which is also cheaper. Where labour is still in good supply, manual placement may still be the cheapest method. However, in the experiments that tested placement, the fertiliser was presumably spread carefully over circles of 2 m radius, whereas in commercial conditions application is often irregular and concentrated, and the nutrients may be less effective.

Broadcasting may be achieved by tractor-drawn spinner applicators or by aerial spreading. In principle, it is difficult to see reasons why their efficiency should differ, except that aerial application does not pose a risk of soil compaction. However, there are often problems with the accuracy of application from the air, and small deviations from the proper trajectory may lead to local zero or double application. Johnston *et al.* (1994) reported that mechanised spreading gave slightly higher yields than either aerial or manual spreading. Mechanised spreading was by far the cheapest method (Table 11.33). A brief review of the spreaders that have been used is given by Lai (2000). Caliman *et al.* (2002b) have strongly encouraged aerial application, on the basis that GPS systems now ensure accurate application. However, the fertiliser material must be appropriate for aerial application, and if so, the cost may be lower than manual application.

None of the more frequent applications gave a better yield than a single application of fertilisers each year (Teoh and Chew, 1985). The same results were obtained under African conditions (Hartley, 1988, p. 526), on a very sandy soil where one might have expected frequent applications to be superior. The storage capacity of the oil palm for nutrients is probably sufficient to control any short-term differences in availability, and in West Africa the very low-yielding palms continued to show responses to single fertiliser applications for a number of years.

11.9.4 Conclusions

This chapter can best be concluded by referring to Ng (1977), who summarised his view of the main principles of fertilising very perceptively. The most important ones were:

- a greater appreciation of the nutrient balance concept in the overall assessment of fertiliser needs (over the whole palm cycle)
- better understanding of gross nutrient uptake in relation to the palm age, development and productivity (net uptake may be more relevant)

Table 11.33 Comparisons of the yields with aerial, mechanised and manual fertiliser spreading, and the resultant costs

Method	Rate	FFB yield (t/ha per year)	Application cost (RM/t)
Aerial application	1	23.01	68.95
	2	24.67	
Manual application	1	23.87	38.60
	2	24.99	
Mechanised spreading	1	25.16	23.50
	2	25.32	
Control	No fertiliser	18.83	
	basal P and Mg only	17.31	
Standard error			
Method	0.357		
Rate with method	0.504		

Data consist of 2 years' pretreatment and 4 years' post-treatment data adjusted for pretreatment variation through covariance analysis.
After Johnston *et al.* (1994).

- improved techniques of assessing soil nutrient supplies and their exploitation, particularly for potassium and magnesium
- greater exploitation of the symbiotic nitrogen fixation system through legume covers
- spreading fertilisers to reach as large a surface area of feeding roots as possible
- maintaining a balance between major nutrients, particularly nitrogen and potassium, and potassium and magnesium
- paying greater attention to micronutrient needs
- ensuring early recognition and treatment of problem areas, such as acid sulfate soils and deep peat soils.

The growing understanding of nutrient management has been built on these propositions, and most issues are now becoming clearer. The outstanding problem remains the low accuracy in assessing fertiliser need by most current methods, so that considerable financial losses can occur quite easily. It is hoped that the newer methods that are being developed will improve this situation.

Chapter 12

Diseases and Pests of the Oil Palm

Until World War II it appears that the oil palm was largely free from serious diseases and pests (Hartley, 1988), but as the area under the crop has expanded, there have been serious, and at times devastating, outbreaks of disease in several parts of the world. Of greatest importance have been the devastation caused by *Fusarium* wilt in several parts of Africa, the considerable losses sustained through dry basal rot (*Ceratocystis*) in Nigeria and associated with *Ganoderma* in old and replanted areas in Asia, and the attacks of fatal yellowing and sudden wither on new plantations in Latin America.

Diagnosis and prevention or cure of some of these diseases have proved difficult. It is not clear in some instances whether a pathogen is involved, or whether the symptoms are a disorder caused by some abiotic factor. The fact that some, perhaps most, diseases only become serious under certain predisposing environmental conditions may further complicate matters. One approach has been to search for resistance to, or tolerance of, the diseases, both within *Elaeis guineensis* material and in interspecific hybrids with *Elaeis oleifera*. Good progress has been made in relation to *Fusarium* wilt with *E. guineensis*, and there is scope for this approach with *Ganoderma*. Hybrids may be tolerant to fatal yellowing, but poor yields limit their value at present.

Attacks by one pest, the leaf miner *Coelaenomenodera lameensis*, have been serious in West Africa, while sporadic defoliation has also been caused by caterpillars and bagworms of various species in Malaysia and Latin America. With the steadily increasing areas under oil palms there has been a general increase, particularly in Asia and America, in the number of pest species recorded; several natural orders are represented, but particularly the Lepidoptera and Coleoptera.

A comprehensive work on diseases was provided by Turner (1981). For pests, Wood (1968a) gave much information of general application on ecology and control, while detailed information on African and American pests is to be found in special issues of the journal *Oléagineux* (Genty *et al.*, 1978; Mariau *et al.*, 1981), and also in Mexzón and Chinchilla (1993). Readers should

refer to specialist works if pesticide treatment is recommended. We have not given details here, because new pesticides are constantly being developed and older ones withdrawn.

Descriptions in this chapter must necessarily be condensed, but reference is made to original papers where greater detail can be found. Nutritional disorders are described in Chapter 11 and this chapter will therefore deal with conditions caused by pathogenic organisms, with important disorders of unknown cause, and with insect and other pests causing damage to the palm.

12.1 DISEASES AND DISORDERS

It is convenient to deal with diseases according to the stage of growth at which the palm is attacked and the organs affected. However, there is much overlap and some diseases have been rather arbitrarily listed for a particular stage of growth. For example, *Cercospora* is primarily a nursery disease, but also occurs in young palms in the field. *Ganoderma* may be characteristic of one age in some regions and of a different age in other regions, while other diseases may have different manifestations at different ages. Information on a number of 'minor' diseases is summarised in Table 12.1. Some of these caused serious losses at one particular time and place, but have not been a problem since. Several were observed in the early days of oil palm cultivation, when fertiliser inputs were low or absent, and poor nutrition was probably an important predisposing factor.

Pathologists set much store by Koch's postulates, conditions which must be met before the cause of a disease is considered proven. In particular, the requirements that typical disease symptoms be obtained after inoculation with a supposed pathogen, and that the pathogen then be reisolated from the inoculated plants, have not been met for several oil palm diseases. Even where Koch's postulates are proven, predisposing environmental factors may still be important.

Table 12.1 Minor oil palm diseases: diseases either causing little economic damage, or of rare occurrence

Disease	Symptoms	Cause	Location	Ref.	Comments
<i>Nursery diseases</i>					
Anthracnose	Necrotic lesions, slow growth	Various (see Ref. 1)	Widespread	1, 2	Treatment similar to <i>Cercospora</i>
Seedling blight	Elongated spots with yellow halo	<i>Curvularia eragrostidis</i> (?)	Malaysia	1	
<i>Cylindrocladium</i>	Brown lesions with white centres	<i>Cylindrocladium macrosporum</i>	Ivory Coast	1	
Leaf spotting		Various (see Ref. 1)	Widespread	1	See Ref. 1 for control recommendations
Nursery spear rot	Rotting of median leaflets of the spear leaf	<i>Phytophthora</i> sp.	Congo	3	Not serious enough to need control
<i>Corticium</i> leaf rot	Rot at base of unopened leaves	<i>Corticium solani</i>	Congo, Malaysia	3	See Ref. 1 for control recommendations
Dry bud rot	Yellow patches on leaves, then dry rot of spear	Unknown	Ivory Coast	4	Similar disease transmitted by <i>Sogatella</i> in coconut (see also Section 12.1.5.5)
Chlorotic ring	Conspicuous mottling	Potyvirus, related to sugarcane mosaic virus	S. America	5, 6	
<i>Mature palm leaf diseases</i>					
Necrotic spot	Brown spots, orange halo, premature withering	<i>Cercospora elaeidis</i>	Africa	7, 9	Different strain of <i>C. elaeidis</i> from that causing freckle (Section 12.1.2.1)
Crusty spot	Orange spots with black crust in centre	<i>Parodiella circumdata</i>	Africa	7	Mainly affects oldest leaves
Genetic orange spotting		Viroid?	Widespread	8	Transmission not demonstrated
Algal leaf spot	Pin-point yellow spots on upper surface	<i>Cephaleuros virescens</i>	Widespread	1, 9	Effect on yield unknown
<i>Other mature palm diseases</i>					
<i>Armillaria</i> trunk rot	Similar to vascular wilt, but leaf bases rot	<i>Armillariella mellea</i>	Congo	10, 11	Incidence has decreased since the 1950s
Basal decay	Sudden death of leaves, following trunk rot	Unknown	Africa, Malaysia	1	Rare
Charcoal base rot	Black rot at base, leaves chlorotic	<i>Ustilina</i> sp.	Malaysia	1, 12	Pathogenicity not proven
Stem wet rot	Internal rotting	Unknown	India	13	

References: 1: Turner (1981); 2: Robertson (1956); 3: Kovachich (1957); 4: Renard and de Franqueville (1989a); 5: Rivera *et al.* (1996); 6: Morales *et al.* (2002); 7: Kovachich (1956b); 8: Hanold and Randles (1991); 9: Robertson *et al.* (1968); 10: Wardlaw (1950a); 11: Moureau (1952); 12: Thompson (1936); 13: Chander Rao (1997).

12.1.1 Diseases of germinating seeds: brown germ

Symptoms and distribution: Brown spots appear on the emerging 'button'. These spread and coalesce as the embryo develops, and the tissues become slimy and rotten. The disease may occur wherever seeds are being germinated.

Cause: Duff identified a variety of *Aspergillus niger* from diseased embryos in Nigeria, and demonstrated pathogenicity by inoculation and reisolation (A.G. Prendergast, pers. comm., 2001). This may not be the only cause, though: Turner (1981) listed 27 fungi associated with the disease, of which *Aspergillus* spp. and *Penicillium* spp. were most frequent. Many are secondary invaders, as are bacterial species.

Control: Brown germ develops most readily under moist conditions at a temperature of 38–40°C; use of the wet heat treatment for germination (see Section 7.1) therefore encourages its spread. Although sanitary measures in the germinator may reduce incidence, the best method of control is to adopt the dry heat treatment method of germination, since the seeds are dry when being heated at 39.5°C, and when germinating they are at around 27°C, a temperature that does not encourage the growth of the organisms.

12.1.2 Seedling leaf diseases

Turner (1981) notes the importance of nursery management in minimising disease susceptibility. With adequate water supplies and balanced nutrition, nurseries in many areas remain largely free of serious diseases, and investigations into disease outbreaks may primarily involve examination of growing techniques, rather than a search for a pathogen. This emphasises the importance of predisposing factors in disease development, as mentioned above.

12.1.2.1 *Cercospora* leaf spot, or freckle

Distribution: *Cercospora* leaf spot is widespread throughout Africa but has not been reported in Asia or America. It is a disease of nursery seedlings which sometimes starts in the prenursery and is frequently carried to field plantings, where it can survive for many years.

Symptoms: The youngest leaves of nursery seedlings become infected and minute translucent spots surrounded by yellowish-green haloes enlarge and become dark brown. Conidiophores emerging through the stomata in the centre of the spots, mainly on the under-surface of the leaf, produce conidia which give rise to

further, surrounding spots. This results in a freckled appearance, but later the lesions coalesce and the tissue dries out to become greyish-brown and brittle. The disease tends to become aggressive as the leaves age, and the process described above may proceed very rapidly at certain periods of the year. In West Africa, this is usually the middle or end of the wet season, and in the following dry season the drying out of the older leaves is much hastened by *Cercospora* incidence.

Cause: *Cercospora elaeidis*. Proof of pathogenicity was obtained by Kovachich (1954) in Congo and Robertson in Nigeria (1956). For details of growth and reproduction of *Cercospora* in the host, the papers of these authors and of Weir (1968) should be consulted. Nitrogen manuring may cause a small increase in the incidence of freckle in the nursery, but potassium substantially reduces it. Small favourable effects of phosphorus have also been noted (Robertson, 1960).

Effect on yield: Duff (1970) showed that *Cercospora* could depress yields by more than 10% over the first 7 years of production. Even moderate attacks materially reduced the green leaf area and might therefore affect early bunch production. Note, though, that quite severe defoliation during the first year in the field may have little effect on subsequent yield (see Section 12.2.1.2). Jacquemard (1998) describes the disease as depressing nursery growth, but not economically important.

Control: The obvious course is to try to eradicate the disease in the nursery and to prevent reinfection of the young seedlings in the field. Jacquemard (1998) recommended spraying with mancozeb and benomyl. In the nursery, if spraying is not done, all old dry leaves and any others badly infected should be removed by pruning. In the field, however, excessive pruning may reduce growth and delay flowering, whereas failure to prune may increase the severity and prolong the incidence of the disease. A compromise pruning standard suggested by Hartley (1988, p. 585) was to remove and burn any leaf that showed dead or badly necrotic areas over more than one-third of its total surface, but it is not clear whether this would control the disease.

Elaeis oleifera progenies planted in Africa have shown a marked susceptibility to the disease; interspecific hybrids are rather less susceptible. There are significant differences between *E. guineensis* progenies in *Cercospora* susceptibility (Robertson, 1963) and, since serious loss of crop through *Cercospora* attack in field plantings has been demonstrated, Duff (1970) suggested that breeding for tolerance would be worthwhile. With good control being obtainable with fungicides, however, it is doubtful whether breeding for tolerance can be justified.

12.1.2.2 Other seedling leaf diseases

Various diseases of minor importance or rare occurrence are listed in Table 12.1. Some nursery diseases, for which many causes (including virus infection) have been suggested but none established, have been constant enough in their symptoms to acquire distinctive names. These include bronze streak, ring spot and infectious chlorosis (which, despite the name, appears

not to be infectious). Turner (1981) gives information on these.

Leaf distortions occur in young prenursery and nursery seedlings at the bifurcate leaf stage (Plate 12.1) and have been described as:

- leaf crinkle, in which the lamina between the veins is folded in lines across the leaf



Plate 12.1 Certain abnormalities of nursery seedlings. (A) Leaf Crinkle; (B) Leaf Roll and (C) Collante.

- leaf roll, in which the lamina is rolled under the leaf, giving it a spiky appearance
- collante, in which the lamina between the veins becomes laterally compressed at a band about halfway along the leaf so as to form a constriction there (Gunn *et al.*, 1961).

Other abnormal conditions that necessitate culling in the nursery are described in Section 7.2.2.4.

Malformed seedlings are not uncommon in the prenursery and are variously attributed to the after-effects of brown germ, or to incorrect orientation of the germinated seed at planting.

12.1.3 Seedling spear and bud rots

Several nursery spear and bud rots have been recorded, but none appears to be serious (Table 12.1).

12.1.4 Seedling root diseases: blast disease

Distribution: Blast has been a serious nursery disease throughout West Africa. It was particularly severe in the Ivory Coast and of considerable importance in Nigeria and Cameroon. The disease has also been recorded from Malaysia (Turner, 1966b), Indonesia, Brazil (Cardoso, 1961) and Colombia, and Turner (1981) considered that it could occur in any country where climatic conditions and nursery techniques are likely to favour its development.

Symptoms: The symptoms of blast disease were described in detail by Bull (1954) and Robertson (1959a). Affected seedlings lose their normal gloss and become dull and flaccid, the leaf colour changing successively to olive green, dull yellow, purple or umber (at the tips) and, finally, with full necrosis and drying out, to a brittle dark brown and grey (Plate XIA). Necrosis of the central spear is usual and death occurs in a few days. In a small percentage of cases the rot may not reach the growing point; the seedling then survives, but as a weak and unacceptable plant. In many of the roots of diseased plants the parenchymatous tissue within the hypodermis has been rapidly destroyed from the tip towards the stem base, the stele remaining loose within the hollow cylinder. When the rate of cortical rotting becomes greater than the rate of production of new absorbing roots, desiccation and death follow very rapidly.

Causes: Two quite distinct causes for this disease have been convincingly demonstrated. Robertson (1959b) showed that it was caused by a joint infection of the roots by two fungi, and satisfied Koch's postulates in proof

of this. Subsequently, it has been demonstrated in the Ivory Coast that an insect vector is involved. Turner (1981) discussed the possibility of there being several causes of blast or of two apparently different causes being linked. The leaf symptoms are essentially those of acute water stress, and might be caused by any severe damage to the roots.

Robertson (1959b) isolated *Rhizoctonia lamellifera* from decaying cortical tissue in the roots, and a *Pythium* species, probably *P. splendens*, from primary infections of the root tips, where it was shown to penetrate the cells and cause their collapse. In laboratory experiments, Robertson (1959b) showed that the *Pythium* may be parasitised by *R. lamellifera*. In inoculation experiments, a mixed inoculum of *Pythium* and *R. lamellifera* produced more extensive root rotting, and the leaf symptoms were more pronounced than with either species individually. Inoculation with *R. lamellifera* alone was only successful when the roots had been artificially damaged, while with *Pythium* inoculation, damage was confined in the root tips. In all of these cases pathogenicity was established by reisolation of the organisms. It was concluded that *R. lamellifera* plays an important part in blast disease in the destruction of cortical tissues and that it gains access either through a prior invasion by *Pythium* sp., which it parasitises, or through root damage from some other cause. The *Pythium* species was thought to be important through its role as a primary invader and its ability to penetrate the parenchyma cells and develop within them.

Subsequent to Robertson's work, quite different results were obtained in the Ivory Coast, where the blast problem had always been severe. It was noted that plants grown in metal cages covered with mosquito netting showed less than 1% blast in comparison with 15% outside in unshaded areas. A polybag nursery trial compared a completely closed cage with very fine netting (to give the minimum shading effect), an open-top cage, plots treated twice weekly with parathion, and unshaded control plots which had natural grass between the bags (Renard *et al.*, 1975). The results were as follows:

	Treatment:			
	Completely enclosed	Open-top cage	Parathion	No treatment
Blast (%) by end of Dec.	0	6	27	46
Blast (%) by end of Jan.	2	9	35	63

These results led to the hypothesis that an insect vector was involved. Later, it was established that the insect was *Recilia mica* (Hemiptera: Delphacidae), for which the grasses *Paspalum* spp. and *Pennisetum* spp. were alternate host plants (Julia, 1979). Julia found that *R. mica* moved to the palm nursery from surrounding grass only in October and November. De Franqueville *et al.* (1991) found that the insects were most frequent in November and December, and introduction of *R. mica* to caged palms gave the highest disease incidence at that time. The exact connection between *R. mica* and blast disease has not been determined. Renard (1981) showed that tetracycline gave good protection, suggesting the possibility that a mycoplasma is involved, but this has not been confirmed.

Control: The precautions that are taken in nurseries against blast are briefly discussed in Chapter 7. The effect of shade in reducing blast incidence has been established, but the provision of shade for large plants nearing the end of their nursery life has disadvantages, and in Nigeria generally proved unnecessary. A significant negative correlation was found between blast incidence and rainfall during the 'short dry' season in August and September (Robertson, 1959a). The blast season normally extends from October to January, and experiments confirmed that irrigation during August and September substantially reduced blast incidence.

An interesting feature of blast disease is the importance of time of attack. It has been shown both in the Ivory Coast (Bachy, 1958) and in Nigeria (Robertson, 1959a) that a relationship exists between blast incidence and the age of the seedlings at the time of attack. If the seedlings are either very young (1–4 months) or old (11 months or over) at the beginning of the blast season, the casualties are few. De Franqueville *et al.* (1991) showed that seedlings with four or five leaves were more susceptible than older seedlings. In seedlings with two leaves the disease developed slowly, but eventually reached the same level as in plants with four or five leaves.

Desmier de Chenon (1979) found that the removal of grasses in the vicinity of the nursery reduced blast incidence; the application of aldicarb monthly from the start of the nursery was also effective and made it possible to eliminate the shade which had always been found necessary in the Ivory Coast (Quencez, 1982).

The control measures for blast in West Africa may be summarised as follows.

1. Time the planting of nurseries to ensure that the blast season has passed before the seedlings reach the susceptible stage. This will involve planting

well-developed prenursery seedlings early in the rainy season, and ensuring their rapid growth.

2. Pay particular attention to irrigation during the short dry season and make sure that polybags have a sufficient, though not excessive water supply throughout the nursery period.
3. Where *Recilia mica* is prevalent, spray out host grasses in the vicinity of the nursery, and apply aldicarb monthly.

De Franqueville *et al.* (1991) tested several insecticides, and found that omethoate was also effective. Clones differ in their susceptibility to blast (IRHO, 1992b), but breeding for resistance would not be a sensible approach to an easily controlled nursery disease.

12.1.5 Adult palm leaf diseases and disorders

12.1.5.1 Crown disease

Distribution: The disease was most prevalent in the Far East, particularly in the early Deli plantations. All but the most severe cases normally recover during the second year after planting, and effects on yield are then not serious.

Symptoms: A palm suffering severely from crown disease has many of its leaves bent downwards in the middle of the rachis; at this point the leaflets are absent, or small and ragged (Plate XVA). These symptoms originate in the spear leaf, where the folded leaflets begin to show a rot of their edges or centre (Kovachich, 1957). This rot spreads throughout the central portion of the leaf so that when the leaf unfolds the leaflets of this section are disintegrating or already missing. The rachis bends at the point where the leaflets are absent. In severe cases all the leaves surrounding the spear may be bent down, and the spear itself may have a rot of its terminal portion which turns brown and hangs down. Under these extreme circumstances, crown disease may have a severe effect on early development and yields. The disease normally affects palms in the second to fourth year in the field, but instances have been reported in the nursery and up to 10 years of age.

Causes: No pathogen has been identified, and it was assumed in the early days that the disorder was physiological and might be inherited. The latter assumption proved correct (see below); with regard to the former it was suggested that palms suffering from the disease have low leaf magnesium contents and that the incidence of the disease might be affected by magnesium and potassium manuring (Hasselo, 1959). Breure and Soebagyo

Table 12.2 Reduction in yield of palms with crown disease

Class	Severity of symptoms	Palms in class (%)	Yield loss/palm (%)		Yield loss/ha (%)	
			1st 6 m	7–38 m	1st 6 m	7–38 m
0	No symptoms	80.8	0	0	0	0
1	Slight	8.0	15.1	2.7	1.2	0.2
2	Mild	6.3	22.8	3.4	1.4	0.2
3	Severe	4.5	36.1	4.5	1.6	0.2
4	Very severe	0.25	54.3	34.0	1.4	0.8
5	Extremely severe	0.12	43.2	27.1	0.5	0.3
Total loss/ha (%)					6.1	1.7

From Dumortier (1998).

Loss per hectare = loss/palm $\times$ palms in class.

(1991) compared two sites, and observed lower leaf boron levels (and rather lower magnesium) at the site with more severe incidence of crown disease.

Thompson (1934) stated that the 'decreased rigidity' of the rachis was due to insufficient lignification of the parenchymatous tissue, and Monge *et al.* (1994) found that the fibres of vascular bundles in the rachis were very thin-walled in affected leaves. The leaves, however, tend to be quite rigid, although bent. Monge *et al.* (1994) considered that crown disease and spear rot might be manifestations of the same disorder. Alvarado *et al.* (1997) also suggested the two were associated, but in their trials with a susceptible progeny, poor drainage reduced the level of crown disease, but increased spear rot incidence (see Section 12.1.7.2). Boron application also reduced crown disease incidence.

Effects on yield: Severity of crown disease varies between environments (Breure and Soebagyo, 1991). In Papua New Guinea (PNG), where incidence can be severe, Table 12.2 shows a yield loss of about 6% in the first 6 months of production, and just under 2% over the next 2.5 years. Breure and Soebagyo (1991) estimated losses of 4.5% over the first 3 years of production in North Sumatra, with the greatest loss in the first year.

Control: De Berchoux and Gascon (1963) showed that pure Deli progenies in the Ivory Coast were highly susceptible. La Mé material, free of crown disease, gave crosses with Delis which were also free of crown disease, but Congo material, which showed several cases of the disease, gave Deli $\times$ Congo crosses with a quarter to a half of the palms showing the disease. The authors postulated that susceptibility to crown disease is due to a single recessive gene. Some examples from their results are given in Table 12.3, showing close agreement with the expected segregations. Thus, it appeared practicable

to select palms that would not produce susceptible individuals in their progeny; in particular, it would be valuable to have *pisifera* shown to be homozygous for absence of crown disease (CC), as the Congo (Sibiti) palm S127P appeared to be.

Blaak (1970b) found that with some palms in Cameroon the expected inheritance occurred. However, other crosses gave segregations that could best be explained by the presence of an inhibitor gene which, when homozygous, suppressed expression of the disorder. Examples from Blaak's results are also given in Table 12.3.

If susceptibility is controlled by only one or two genes, then its elimination from a breeding programme should be easy, although Blaak (1970b) pointed out that the presence of an inhibitor gene complicates selection, since detection of a palm of *cc* genotype (susceptible) is only possible by test crossing with a palm that is known not to have the inhibiting gene. The losses noted by Dumortier (1998) are quite small, but 6% extra crop over the first 6 months of production is clearly worth having. However, Dumortier showed that *pisifera* DM742.207 transmitted crown disease susceptibility to its offspring, and yet it consistently gave the highest yielding progenies in most environments (Dumortier and Konimor, 1999). Thus, it is understandable that some oil palm breeders have not regarded eliminating susceptibility from their programmes as being very important.

12.1.5.2 Leaf wither, Pestalotiopsis leaf spot or grey leaf blight

Distribution: A virulent type of leaf withering has been troublesome in parts of Colombia, Ecuador and

Table 12.3 Incidence of crown disease in various crosses in the Ivory Coast and Cameroon, and expected segregation with and without Blaak's inhibitor gene; expectations shown are those if the inhibitor were dominant

Presumed genotypes	Cross	Observed (%)		Expected (no inhibitor) (%)		Expected + inhibitor (%)	
		Without	With	Without	With	Without	With
<i>de Berchoux and Gascon (1963)</i>							
cc × cc	D115D selfed	0.5	99.5	0	100		
CC × cc	L10T × D115D	100	0	100	0		
cc × CC	D115D × S127P	100	0	100	0		
Cc × cc	L219T × D115D	57	43	50	50		
Cc × cc	S7T × D115D	52	48	50	50		
Cc × Cc	L219T × D10D	81	19	75	25		
Cc × Cc	L239T × D128D	71	29	75	25		
<i>Blaak (1970b)</i>							
Cc ii × Cc ii	1.2229 selfed	79	21	75	25	75	25
Cc II × Cc ii	3.417 × 1.2229	77	23	75	25	75	25
Cc II × Cc II	3.417 selfed	100	0	75	25	100	0
Cc ii × Cc ii	5.37 selfed	76	24	75	25	75	25
Cc II × Cc ii	3.415 × 5.37	96	4	75	25	100	0
Cc II × Cc II	3.415 selfed	100	0	75	25	100	0
Cc li × Cc ii	15.4624 × 5.1295	85	15	75	25	87.5	12.5

From de Berchoux and Gascon (1963) and Blaak (1970b).

Honduras, and has caused much defoliation, with significant effects on yield. It is also commonly seen in Colombia on *E. oleifera* palms.

Symptoms: The first symptom is the appearance of small brown spots with yellowish haloes. These spots soon coalesce into brown necrotic areas which spread over the leaflet tissue and later become grey and brittle (Plate XIX). There is a sharp line between the brown and grey areas and in the latter a species of *Pestalotiopsis* is found, black specks indicating the location of spore-bearing acervuli (C.W.S. Hartley, 1974, unpubl.).

Cause: The disease has been described as *Pestalotiopsis* leaf spot and grey leaf blight in Malaysia, but there the fungus is only associated with old and near-moribund leaves and is not considered of economic importance (Turner, 1981). The severity of the attacks in Latin America seem to be due to the easy access given to the young leaves by the feeding activities of insects, but it is also possible that the strains of the *Pestalotiopsis* species involved are more aggressive.

Genty *et al.* (1975) showed that *Leptopharsa gibbicarina* (Hemiptera: Tingidae) was the principal means of infecting young leaves. This insect punctures the leaflets alongside the midribs, producing whitish spots with their surrounds stained with excrement (Genty *et al.*,

1983). In Ecuador, *Peleopoda arcanella* has been implicated in assisting infection of the leaves by *Pestalotiopsis* sp. (Turner, 1981). Two species of *Pestalotiopsis* are the usual entrants, but species of *Helminthosporium*, *Curvularia* and other genera may also gain access to the leaflets.

Effects on yield: The disease has caused considerable defoliation on some plantations and, as would be expected, this has been followed by serious yield decline. Bunch production falling from 18–20 to 12–15 t fresh fruit bunch (FFB)/ha in adult areas, and from 11 to 7–8 t/ha in young plantings has been reported (Jiménez and Reyes, 1977).

Control: The attacks on moribund tissue in Africa and Malaysia have often been associated with magnesium deficiency symptoms (Bull, 1961a). In Colombia, the disease is less severe if potassium and magnesium are in balance (P.L. Gomez, pers. comm., 2001).

Control of *L. gibbicarina* by aerial spraying of propoxur, fenitrothion or phosphamidon has had considerable success in checking the disease, but more recently trunk injection or root absorption of monocrotophos has been advocated; as noted in Section 12.2.1.4, these methods of application have advantages in terms of selectivity. Monocrotophos injection has also been

successful in Honduras (Vessey, 1981). The possibility of biological control has been studied (Genty *et al.*, 1983; Guerrero, 1985), and Mendez (2000) described successful management of the disease by encouraging *Crematogaster* ants and using *Beauveria* and *Paecilomyces* fungi to control the insect vector.

12.1.5.3 White stripe

Distribution: The condition is sporadic and, in Asia, is said to be more common on alluvial soils, particularly organic clays or mucks. Affected palms have reduced yield.

Symptoms: Narrow yellowish-white stripes are found on each side of the leaflet midrib and extending its whole length. The stripes are sharply divided from the adjoining green (often dark green) tissue. Affected palms usually recover, and Rajaratnam (1972b) reported that the chlorotic tissue might turn green after about 7 months and that the symptom was more prominent in young leaves than in old. He also showed that chlorosis was due to failure of the palisade mesophyll cells to elongate and that apparent recovery was through an increase in the chlorophyll content of the spongy mesophyll, and not through development of the palisade cells. Turner (1981) stated that symptoms are more severe in Malaysia than elsewhere, and that typically they appear at 2–3 years of age, becoming more severe at 3–5 years and then becoming chronic.

Effects on yield: Moderately affected palms yielded 15% less than healthy neighbours, and severely affected palms nearly 50% less (Rajaratnam, 1972b). However, Tohiruddin *et al.* (2002) found that yield was sometimes positively correlated with white stripe incidence (see below).

Cause: It has been suggested that the disorder is of genetic origin. A certain *tenera* × *dura* cross showed similar percentages of white stripe when planted in Ivory Coast and in East Cameroon; also certain Deli selfs in Ivory Coast showed the symptoms while others did not (Ollagnier and Valverde, 1968; Gascon and Meunier, 1979). However, the general view is that the cause is nutritional: boron deficiency and a high leaf N:K ratio have both been suggested. In boron-deficient seedlings, Rajaratnam (1972a) found chlorotic patches, in which the palisade mesophyll had not developed, but the patches did not form stripes. In one trial, palms showed a degree of recovery when boron was applied, but in another they did not.

Turner and Bull (1967) considered that a nitrogen:potassium imbalance was the main cause of white stripe, but Rajaratnam (1972b) observed the

disorder in palms with N:K ratios well below that suggested as critical by Turner and Bull. Tohiruddin *et al.* (2002) found a positive correlation of white stripe incidence with N:K ratio in only one of five fertiliser trials studied. In that trial, there was a negative correlation with leaf K content, and a stronger correlation with rachis K content (rachis K is more sensitive to applied K than leaf content; see Section 11.4.2.2). In unfertilised palms in that trial, rachis K content was below 0.6%, much lower than in the other trials. The correlation of white stripe incidence and yield was negative and statistically significant.

In two other trials, where leaf N content exceeded 2.8%, white stripe incidence was positively correlated with leaf N content, and positively (but not significantly) correlated with yield. There were no correlations with leaf boron content. These results support the N:K imbalance hypothesis, but suggest that the leaf N:K ratio is not an adequate indicator of the imbalance.

Treatment: Turner (1981) suggested substantial applications of potash with reduction of nitrogen applications, but Tohiruddin *et al.* (2002) distinguished between white stripe caused by low K status, and by high N status. Where rachis K is low, potassium fertiliser should be applied. Where leaf N exceeds 2.8%, reducing N input may reduce white stripe incidence, but it is also likely to reduce yield. In this situation, symptoms can be expected to disappear with time, since as palms grow older, leaf N content tends to fall, and K reserves increase.

12.1.5.4 Leaf mottle (*mancha anular*)

Distribution: This condition, which often leads to death of the palm, has been reported from Ecuador and Peru and is described by Turner (1981). It has been called ring spot, but that term is already used for a nursery disease.

Symptoms: When the spears open they fail to become fully green, and spots of pale tissue remain. These may be circular, or elongated and almost rectangular, and may form almost continuous streaks. Younger fronds then become chlorotic. This leaf symptom is followed by the rotting of the root system and spear, although Turner (1981) considered the spear rot to be secondary. Developing bunches may also rot. Palms may die within 3 months of the first symptoms, but some palms continue to grow and yield for several years, despite showing leaf symptoms.

Cause: Martínez (1988) suggested that a virus might be the cause, but this has not been confirmed. Renard and de Franqueville (1989a) described nursery dry bud

rot as being similar (see Table 12.1). A similar disease of coconuts is transmitted by two species of *Sogatella* (Homoptera: Delphacidae) (Julia and Mariau, 1982).

Treatment: Fungicides, insecticides and antibiotics have been tested without effect. Diseased palms tend to be scattered throughout a field, but incidence is much higher with dense grass cover than with a legume cover (Dzido *et al.*, 1978). A good leguminous cover should therefore be maintained in areas subject to this condition.

12.1.5.5 Patch yellows

Distribution: This disease appears to be confined to Africa, where it is widely distributed, though sporadic and affecting only a small proportion of palms. A condition in Malaysia known as wither tip, from which both *Fusarium oxysporum* and *F. solani* have been isolated, was described by Turner (1981) who suggested that it was allied to patch yellows.

Symptoms: Infection takes place in the unopened spear leaf and for this reason the lesions at the sites of infection appear opposite each other on the leaflets when the leaf opens (Plate XIB). The lesions are circular or oval with rings of pale yellow, sometimes with brown centres. The patches may appear all along the lamina. Later, the centres of the patches dry out and drop away, giving a typical 'shot-hole' appearance, or, if the patches are towards the edge of the leaflets, a raggedly indented appearance. The purely yellow patches persist and darken, and can be seen to have small orange spots within them (Bull, 1954).

Cause: Wardlaw (1946a) reported that, following the discovery of *F. oxysporum* associated with vascular wilt disease, a second strain of *F. oxysporum* which closely resembled the first had been shown to be associated with patch yellows in Congo. Kovachich (1956a) later proved its pathogenicity. Prendergast (1963) found that a patch yellows strain of *F. oxysporum* did not cause vascular wilt in the nursery test (see Section 12.1.6.2 below).

Control: The disease affects up to 1.8% of palms in the areas where it is found, and evidence for genetic susceptibility was provided in Kovachich's pathogenicity tests. In Nigeria, a small proportion of families were susceptible (A.G. Prendergast, pers. comm., 2001). Kovachich suggested selection to eliminate susceptible lines, but the disease does not seem to be sufficiently serious to justify this.

12.1.5.6 Minor leaf diseases

The oil palm leaf is susceptible to patchy discoloration and necrosis from a variety of minor pathogens, some

of which are listed in Table 12.1, and to surface covering by epiphytic and saprophytic organisms. These often cause the older leaves to appear far from healthy, but as the oldest leaves contribute relatively little photosynthetically, the effects may be small.

Black 'sooty mould' is often found to grow on the older leaves of adult palms and occasionally spreads over a large proportion of the leaf surface, giving the palms a blackish-grey appearance. Sooty moulds usually grow as epiphytes on honeydew, the exudate of partially digested plant sap from plant lice, but it is not certain whether this is always the case in oil palm (Wood, 1968a).

Several of the most common fungi to be found in Africa as constituents of the epiphytic flora are listed in Turner's *Micro-organisms associated with oil palm* (1971). Among these, the Ascomycetes *Apiospora* sp., *Meliolinella elaeidis* and *Meliola elaeis* may be mentioned. *Meliolinella elaeidis* is recorded as also being found in America (Costa Rica) on *E. oleifera*. Epiphytic flora may appear on the upper or lower surface of the leaves. In West Africa the black mould usually found on the upper surface consists of discrete circles of about 5 mm diameter; on the lower surface the black mould is in irregular patches of less dense material. In Malaysia, sooty moulds of *Brooksia*, *Ceratomyrium* and *Chaetothyrium* spp. develop on insect secretions on the leaves (Williams, 1965; Turner, 1981). *Brooksia tropicalis* is common in Africa.

Lichens are often found among the epiphytic flora on oil palm leaves, forming small grey-green encrustations on the upper surface of the leaflets (Turner, 1971).

12.1.6 Stem and root diseases

Root and stem diseases are characterised by fracture and drying out of fully developed leaves, leaving the spear leaf and some surrounding leaves standing erect. These early symptoms may be accompanied by a change in colour, drying out or wilting of one of the more erect younger leaves; bud and spear rots tend to be characterised by symptoms in the centre of the crown. The spear leaf may be directly affected or the surrounding leaves show a sudden chlorosis. Successive spear leaves may be shortened, have peculiar 'little leaf' formations, or cease to develop, leaving a palm with an empty centre. These general symptom differences between stem and root diseases on the one hand, and bud and spear rots on the others give a rough guide when deaths occur or alarming disease symptoms appear, but dissection of the palm must follow to determine exactly where the site of destruction is. The site of decay with the root and stem diseases is the bole, trunk

or roots, the disease killing the palm by denial of water and nutrients to the crown. Bud and spear rots, in contrast, kill the palm by growing towards and reaching the single growing point.

12.1.6.1 Dry basal rot

Distribution: This disease appears to be confined to West Africa and, although the pathogen is a common soil inhabitant, the disease was not discovered in epidemic form until 1960. One estate in Nigeria was devastated and thereafter minor outbreaks occurred in several parts of Nigeria, West Cameroon and Ghana. In the first, epidemic deaths were common, but recovery then became more usual and further serious outbreaks have not been reported.

Symptoms: The foliar symptoms, which usually appear at the end of the dry season, are preceded by extensive bunch and inflorescence rot. The rachis of certain leaves then becomes fractured submedianly, although the leaflets remain green for a considerable period before they eventually die (Plate 12.2A). Occasionally, a young leaf high up in the centre of the crown becomes necrotic and dries out, and this precedes the necrosis of the older leaves. It is quite common for a complete ring of leaves to exhibit the submedian fracture while the upper leaves are still erect, and this gives the newly affected palm its characteristic appearance. Later, the upper leaves and the spear will be similarly affected and the palm dies, or it may make a recovery at any stage. A palm that survives may take several years to come back into bearing. Attack has usually been on palms that have recently come into bearing, but 10-year-old palms have also been affected.

The characteristic internal symptom of the disease is a dry rot at the base of the trunk (Plate 12.2B). This rot is well established by the time the primary leaf symptoms are apparent. In the transition zone between rotted and healthy material many vascular bundles are necrotic, and it is possible to trace infection from an infected root or leaf base into the base of the trunk.

Cause: The cause of dry basal rot was shown by Robertson (1962a,c) to be the ascomycete *Ceratocystis paradoxa*, the imperfect stage of which is known as *Thielaviopsis paradoxa*. The latter has been implicated in fatal yellowing (Section 12.1.7.2). *Ceratocystis paradoxa* is a soil inhabitant widely distributed throughout the tropics of Africa and Asia, and causes diseases of several other crops. Its sudden appearance in West Africa as the cause of a serious condition was unexpected and gave rise to investigations on conditions conducive to its spread. An epidemic at Akwukwu in Nigeria occurred on acid sands soils with an unusually



Plate 12.2 Dry basal rot, *Ceratocystis paradoxa*. (A) A severely infected palm showing sub-median fracture of the lower leaves. (B) A palm showing external symptoms of the disease, dissected to expose the dry rot at the base of the trunk.

low clay content at depth (15–17% at 2 m), and minor outbreaks at the Nigerian Institute for Oil Palm Research (NIFOR) Main Station also occurred on

fields with little clay in the profile. This led to the belief that incidence might be connected with soil–climate relationships. A further outbreak at NIFOR in 1967 followed a severe dry season. Incidence varied between fields from 0.1 to 10%.

Two features of the spread of the disease are important. In the outbreak at Akwukwu many deaths occurred in the first 2 years, amounting to about 30% in one area. Thereafter, very few deaths occurred and there was considerable recovery; although new infections occurred, these did not give rise to many further deaths (Hartley, 1988). All the palms that recovered were bearing bunches by 3 years after the last survey (Rajagopalan, 1965). The other feature of this disease at the NIFOR Main Station was that incidence in one field of 9-year-old palms was mainly confined to progenies having the same female parent. In Robertson's pathogenicity tests he found he could infect all seedlings through a root dipping technique; nevertheless, inoculated progeny lines planted in the nursery showed marked differences in disease incidence (Robertson, 1962b). Selection for resistance is therefore a promising line for the future should the disease once more become important.

12.1.6.2 *Fusarium wilt or vascular wilt*

Since its description by Wardlaw (1946b) in Congo, *Fusarium* wilt has been considered one of the most menacing of oil palm diseases. The disease has been observed on plantations in Congo, Nigeria and West Cameroon, in the Ivory Coast, and elsewhere in West Africa. It has also been recorded in Brazil and Ecuador. Its effects are serious: in the acute form the palm rapidly dies, while chronically affected palms yield little or nothing.

Symptoms: In the more usual, chronic form of the disease in mature palms, the older leaves become desiccated and the rachis breaks near the base or at some distance from the base, the ends of the leaves hanging downwards. This feature has been used to distinguish the disease from *Ganoderma*, in which the leaves collapse at the base and closely cloak the stem. The disease usually proceeds gradually along several leaf spirals, with younger leaves becoming successively affected. The erect and still green leaves in the crown become successively more reduced in size and are often chlorotic, and the palm may stay in this state for several years before the crown eventually collapses.

Occasionally, a mature palm suffers a rapid death through an acute attack. The leaves dry out and die rapidly while still in an erect position, and then snap off about 1 m or more from the trunk, usually during strong winds (Plate XIIB). The remaining

leaves die quickly. All stages between the acute and chronic forms are encountered.

Symptoms of the disease in young palms in which no trunk has yet been formed are somewhat different. In these palms the 'lemon frond' symptom is frequent: a leaf somewhere in the upper middle part of the crown (fourth to 15th leaf) develops a bright lemon-yellow colour before drying out from the tip to the base. Leaves at about the same level then turn yellow and dry out, to be followed by some of the younger leaves, which will die while many of the older ones remain green. Newly developed leaves become successively smaller (Plate XIIA), and death of the whole palm usually takes less than a year. It should be noted that the striking lemon-frond symptom is not always seen, and in southern Congo a general yellowing of the leaves before death was more usual.

Internal symptoms of the disease are quite distinctive (Plates XII, XIII). The vascular bundles are normally pale yellow or whitish, but when diseased they become brownish-grey or black, and a cross-section of the trunk therefore shows a speckled appearance (compare Plates XIID, E). Discoloration, which is associated with the presence of gum, is confined to the xylem vessels (Plate XIIE); blackened fibre strands do not indicate vascular wilt. Such blackening often occurs in older palms and sometimes in other conditions, and the inexperienced observer can therefore be misled into a wrong field diagnosis. Moureau (1952) pointed out that although discoloration of the xylem vessels is normal in palms over 20 years old, in these palms the blackening decreases towards the top of the palm instead of becoming accentuated as in the case of wilt. In palms with acute wilt, A.G. Prendergast (pers. comm., 2001) found large cavities, often more than 30 cm across, in the stem within 2 m below the crown; these cavities were filled with a dense mass of *Fusarium* mycelium.

Drying-up of the leaves and death of the palm are caused partly by the destruction of the roots and partly by the blocking of the xylem vessels by gels and gums. Diseased vessels may at first occur in only one section of the stem base, and this probably accounts for leaf symptoms being confined at first to certain spirals. Xylem vessels in the centre and at the top of the stem then become diseased and the symptoms spread across the stem, so that a large proportion of the vessels at the top are affected. In young palms, up to 6 years old, diseased vessels are usually widely dispersed throughout the base.

The disease is normally recognised in the field by the external symptoms, but Mepsted *et al.* (1991) showed that the internal symptom of vascular browning could be detected non-destructively by taking tissue samples

with an auger (Plates XIIC, D). Using this method, they found that 25% of a sample of palms, classed as healthy by external appearance, showed internal symptoms of the disease (latent infection). Buchanan (1999) used the auger method, and found a poor correlation between external and internal symptoms. In one palm family, 54% of apparently healthy palms showed internal symptoms, while, conversely, 40% of palms with external symptoms showed no internal browning. Buchanan noted that simultaneous infection by *Cercospora* and *Ganoderma* may produce external symptoms somewhat similar to those of *Fusarium* wilt, so erroneous identification of wilted palms may partly explain his results.

Palms may recover, and recovery has become increasingly common as plantings of tolerant material are extended (Renard *et al.*, 1991).

Cause: *Fusarium oxysporum* f.sp. *elaeidis* (abbreviated below to *Foe*). One isolate from Congo was found to be *F. oxysporum* var. *redolens* (Ho *et al.*, 1985). The pathogen is soil borne and it usually enters the palm through the roots, growing along the stele, which becomes blackened. Infection can take place through wounds in the stem base and through uninjured roots (Kovachich, 1948). Renard (1970) considered that entry of the mycelium was much impeded by lignification even with wounding and that rapid infection was mainly through the transmission of spores in the vascular system. Locke (1972), working with seedlings, showed that the pathogen is confined to the conducting elements of the xylem (Plate XIIIIB) and can reach the stele from the tip of a lateral root or the damaged cortical tissue of a pneumatophore. From the roots the mycelium penetrates into the xylem vessels of the vascular strands, where conidia and chlamydospores are also found. Locke considered that the plant had little defence against serious infection in spite of resin formation and tyloses (Plate XIIC). However, Paul (1995) indicated that in resistant genotypes, gels and tyloses were produced earlier and accumulated to higher levels, and fungal colonisation was restricted compared with susceptible genotypes. In the latter, production of gels and tyloses was delayed and the fungus rapidly colonised the host.

Distribution: The first recording of the disease was briefly described by Wardlaw (1950b) as follows. 'During a visit to the Belgian Congo in 1946 I observed a wilt disease of the oil palm (*Elaeis guineensis*), and isolated *Fusarium oxysporum* from the necrosed vascular strands. In 1947, Messrs. S. de Blank and F. Ferguson, in a private report, announced the presence of this disease in Nigeria and submitted cultures to me for identification; and in 1948 I was able to confirm their diagnosis during a visit to the affected plantations.'

Pathogenicity was confirmed by Fraselle (1951). Thereafter, *Fusarium* wilt was found on several plantations in Nigeria and West Cameroon, in the Ivory Coast, and elsewhere in West and west Central Africa. The disease has been recorded in Brazil (van de Lande, 1983) and Ecuador (Renard and de Franqueville, 1989b), and Flood *et al.* (1989) confirmed the pathogenicity of a Brazilian isolate by inoculation of clonal plants. Dossa and Boisson (1991) showed that, while *Foe* strains from Africa were in many different 'vegetative compatibility' groups, strains from Brazil and Ecuador were in the same group as strains from Benin and the Ivory Coast. This close relationship was confirmed with restriction fragment length polymorphism (RFLP) markers (IRHO, 1992b). It is thus likely that the disease was introduced to South America from Benin or the Ivory Coast, probably on seed, as it has been shown that spores of *Foe* can be spread on seed (Locke and Colhoun, 1973; Flood *et al.*, 1990).

Incidence and spread of the disease: In southern Congo, the greatest devastation occurred in replants. In West Africa the disease was largely confined to plantations, particularly replants, and for a long time was not much noticed in the groves. However, Aderungboye (1982) found that it was widespread in the drier Ogun and Ondo states of Nigeria, but infrequent or absent in the high-rainfall areas of the south-east. Oritsejafor (1989) found that the average incidence in Nigeria was 0.77% in palm groves and 1.35% in plantations. The disease is less frequent in plantations on forest land than on former savannah (de Franqueville, 1991); in the latter, the disease usually takes the chronic form, whereas after forest the acute form is more common.

In plantations in southern Congo, and in Nigeria in replants, wilt is commonly found in young palms that have recently come into bearing. However, in West Africa the disease has also attacked older palms that have been in production for 10 years or more (Prendergast, 1957). Renard and de Franqueville (1989b) indicated that disease development depends on the previous history of the site. In new plantings, the first cases may not be seen until 6–10 years after planting, but in replants in previously infected areas, losses may occur within a year of planting. De Franqueville and Renard (1988) found that wilt incidence in a replant was correlated, not with total losses in the old stand, but with the percentage of previously infected palms which were still living at the time of replanting.

Prendergast (1957) stated that healthy, vigorous palms in good soil suffered little from the disease and he showed that, in areas of potassium deficiency, incidence was substantially reduced by the application of potassium fertiliser. This finding was confirmed in experiments in both

Table 12.4 Yield of palms with missing neighbours at Binga, Congo. The main cause of vacancies was death from *Fusarium* wilt

	Missing neighbours				
	0	1	2	3	4
Yield (kg FFB/palm) for palms without symptoms	93.0	98.5	104.5	77.9	15.7
Yield as % of that of palms without missing neighbours	100	106	112	84	17
Number of palms in class	400	179	23	8	1

From Dumortier *et al.* (1992).

the Ivory Coast and Benin (Ollagnier and Renard, 1976). In the nursery test, in contrast, Prendergast (1963) found that nitrogen reduced susceptibility, but potassium had no effect. Ho *et al.* (1985) found that drought stress increased the severity of symptoms in seedlings.

Prendergast (1957) showed that diseased palms occurred in pairs more frequently than would be expected by chance, indicating infectious spread between neighbouring palms. Dumortier *et al.* (1992) found that palms with missing neighbours, in an area where the main cause of death was *Fusarium* wilt, were more likely to have wilt themselves than those without missing neighbours: of 1600 palms without missing neighbours, 17% had wilt, compared with 24% of 1000 palms with one or more neighbours missing. Only 18 palms had three neighbours missing, but 35% of those had wilt. It has generally been assumed that the disease is soil borne, but Moureau (1952) mentioned aerial spread by spores, and Cooper *et al.* (1989) showed that the pathogen sporulates profusely on male inflorescences, and thus could be spread by spores.

Effects on yield: Acute wilt kills the palm, but Prendergast (1957) observed that infection rates as high as 20% had no apparent effect on yield, and suggested that this was due to yield compensation by palms adjacent to vacant points. However, Dumortier *et al.* (1992) compared the yields of apparently healthy palms, with and without missing neighbours, and found that, although yield did increase slightly in palms with one or two neighbours missing (Table 12.4), the increase was not sufficient to compensate for the missing palms. When more than two neighbours were missing, yield was depressed (although the number of palms with more than two neighbours missing was small). If this depression is real, an explanation could be that palms with several neighbours missing are themselves infected (see above). Yield in the year before a palm died from acute wilt was only 54% of that of healthy palms, while palms with chronic wilt gave a yield less than 30% of that of healthy palms. The effects of deliberate and systematic thinning on yield are discussed in Chapter 9,

where it is concluded that, at the planting densities most widely used, the yield increase from palms adjacent to gaps is unlikely to be sufficient to compensate for the palms removed. This is even more likely to be true for the patchy thinning that would result from disease. Thus, it appears likely that any incidence of acute wilt will reduce yield.

With chronic wilt, palms remain alive and may recover. Renard *et al.* (1993) looked at the effects of chronic wilt on the yields of four classes of palms:

- healthy palms
- palms with typical chronic wilt symptoms
- palms which had had the disease but had recovered
- palms with internal signs of infection (browning of the vascular tissue) but no external symptoms, described as 'latent infection'.

They estimated yield losses due to the disease as 15% in a susceptible cross and 6% in a tolerant cross (Table 12.5). The difference was attributable to lower yields from, and a larger number of, recovered palms in the susceptible cross compared with the tolerant cross. In both crosses, palms with latent infection yielded much the same as healthy palms. Although healthy trees of the susceptible cross gave a slightly greater yield, overall yield was greater from the tolerant cross.

Physiology of diseased palms: In nursery seedlings, the main symptoms are a reduction in petiole length and leaf area. Mepsted *et al.* (1995a) observed symptoms of water stress in infected nursery palms (closed stomata, lower leaf water potential, greater resistance to water flow from stem to leaf), but they considered that water stress was not the cause of stunted leaf development, because stressed but uninfected plants did not show stunted growth. Application of a gibberellin inhibitor, paclobutrazol, caused stunting symptoms similar to those of *Fusarium* wilt. Application of gibberellic acid to infected palms restored petiole length to normal, but had no effect on leaf area. The authors concluded that wilt symptoms might be due, at least in part, to an upset in gibberellin metabolism.

Table 12.5 Effects of chronic *Fusarium* wilt on yield.
The weighted mean yield is (yield as % healthy) $\times$ (palms in class)

Class of palm	Yield (kg/ha per year)	Yield as % healthy	Palms in class (%)	Contribution to yield (tFFB/ha.yr) (143 palms/ha)
<i>Cross L2T × D115D (tolerant)</i>				
1. Healthy	111.8	100	75	11.99
2. Chronic wilt	35.6	32	3	0.15
3. Recovered from wilt	90.8	81	13	1.69
4. Latent wilt	107.4	96	8	1.23
5. Dead	0	0	2	0
	Weighted mean: 94			Total: 15.06
<i>Cross L2T × D10D (susceptible)</i>				
1. Healthy	121.4	100	61	10.60
2. Chronic wilt	26.4	22	4	0.15
3. Recovered from wilt	79.4	65	27	3.07
4. Latent wilt	113.4	93	6	0.97
5. Dead	0	0	2	0
	Weighted mean: 85			Total: 14.79

From Renard *et al.* (1993).

Chronic and acute wilt: Mepsted *et al.* (1995b) found that water stress symptoms in nursery palms were much more severe in the older leaves, opened before the palms became infected, than in the younger, stunted leaves. They suggested that stunting might be an adaptation by the palm to reduce the water stress caused by occlusion of the xylem vessels, and speculated that, in field palms, failure to adapt in this manner might result in the acute form of wilt, while in palms that were able, or had time, to adapt, the chronic form would result. Prendergast (1963) and de Franqueville (1991) found no obvious difference in behaviour in the nursery test between *Foe* strains isolated from acutely infected palms, and from palms with chronic wilt. This suggests that the difference between forms of the disease may be in the host reaction. According to de Franqueville (1991), however, the acute form is more frequent in plantations on forest land than on former savannah. Such a difference is more easily explained in terms of pathogen strains than by host reaction, but differences in climate could be a factor.

Control: In Congo, the destruction by fire of all diseased palms and their neighbours was recommended and the replanting of areas where *Fusarium* wilt had been prevalent was discouraged (Moureau, 1952). In the Ivory Coast, de Franqueville and Renard (1988) stated that all trees infected with chronic wilt must be removed at least 5 years before replanting. However, they were unsure how early such removal should start, and suggested as a compromise the removal of any infected palms not producing at least one bunch per year. *Calapogonium*

caeruleum or *Pueraria* as cover increases wilt incidence, and Renard and Quillec (1983) recommended planting grass species such as *Brachiaria* instead, suggesting that competition for nitrogen between the grass and the palm discouraged *Fusarium* infection. Competitive grasses may themselves depress palm yield, though, and the recommendation of de Franqueville and Renard (1988) to keep a strip of bare soil on either side of the row of young palms seems preferable. Turner (1981) considered that any effect of fungicides was likely to be short lived. Renard and de Franqueville (1991) found a significant increase in wilt in plots mulched with EFB, and a reduction when potassium fertiliser was applied.

Breeding for resistance: The most promising method of control is by the breeding of resistant lines. Prendergast (1963) was the first to develop a technique for the screening of seedlings for tolerance to the disease at the nursery stage (Plate XIII A); his method was adopted with little modification by Renard *et al.* (1972). The method involves inoculation by pouring a suspension of *Foe* spores onto the bulb of the seedlings or the exposed roots around the collar. Prendergast (1963) described the symptoms in nursery seedlings in detail, and showed that results were not much affected by the size of the seedlings at the start of the test. He also noted the importance of the inoculum level and the time of evaluation: with too light an inoculum, or too early evaluation, few cases might be observed, and differences would be hard to detect. However, if the inoculum was very heavy or evaluation was late, all plants might die.

The standard nursery test requires large numbers of plants of each family, and hence large areas of nursery space; Prendergast (1963) used 40 seedlings per family, and Renard *et al.* (1991) up to 160. Locke and Colhoun (1974) developed a method of inoculating very young seedlings grown in compost with two known levels of inoculum, and then compared their growth with that of seedlings grown in uncontaminated compost. Determinations were made of the number of propagules in the soil so that subsequent inoculations could be related to normal soil levels. The fungus was recovered from progenies showing both large and small reductions either in weight per plant or in 'leaf area product'. It was demonstrated that some progenies were tolerant of infection in lightly contaminated compost only, and some in both lightly and heavily contaminated compost; others showed high susceptibility at both levels. A high degree of repeatability was attained, but this method does not seem to have been adopted by oil palm breeders.

Flood *et al.* (1989), using clonal plants, were able to reduce the numbers required to only 12 plants per clone, by using inocula with a known, constant concentration of fungal spores, and by detailed classification of the severity of symptoms on each plant.

Sound statistical analysis of the data from nursery inoculation trials is essential, if reliable results are to be obtained (reviewed by Porter, 1989). In all trials, the percentage of infected plants in each family has been recorded. Prendergast (1963) then divided the progenies in a trial approximately into quartiles, or classified as resistant those that differed from the mean by at least one standard error. Renard *et al.* (1972) calculated a 'wilt index', as the percentage of wilt-infected plants in a progeny divided by the mean wilt percentage of all the progenies in the trial. The best method appears to be that described by de Franqueville (1984). A wilt index was calculated in the same way as by Renard *et al.*, but after angular transformation of percentages for individual plots, data were statistically analysed, and progenies were only accepted as resistant if they had significantly lower losses than either the mean of the trial, or standard crosses of known performance.

An alternative to the standard nursery test was developed by Mepsted *et al.* (1995c). This involved inoculation of 2.5 cm sections from near the tip of the rachis, by immersion in a suspension of *Foe* spores under mild vacuum. Within 8 days, rachis sections from susceptible clones turned completely brown internally, whereas those from resistant clones showed little or no browning. This test is much faster than the nursery test, which takes several months. In addition to speed, the method has the great advantage that it can be applied to individ-

ual palms. The nursery test is based on the average performance of a group of palms, so the only way to screen individuals is as clones, or by studying the progeny of a self-pollination. Subsequent experience has shown that the rachis test only works well on palms that are in good health; nutrient-deficient palms, or palms infected with *Cercospora elaidis*, showed severe browning in both susceptible and resistant clones (Buchanan, 1999).

The inheritance of resistance is discussed briefly in Section 5.3.5. Prendergast (1963) and de Franqueville (1984) considered that the most susceptible families could be quite consistently and repeatably identified by the nursery test. De Franqueville also found a reasonable correlation between results of the nursery test and disease incidence in the field, in a heavily infested part of Congo. Renard *et al.* (1972, 1980) also showed that tolerant seedlings in the nursery test give rise to palms with a low incidence of wilt in the field.

Porter (1989) described resistance breeding in Congo, where selection was based primarily on performance in disease-infested fields (Plate VID), backed up by the nursery test. He gave examples of parents consistently transmitting resistance or susceptibility to their offspring in field trials. For example, 14 crosses derived from palm 69MAB (see Fig. 5.4) were all more resistant than the trial mean, 12 of them significantly so. Conversely, of seven crosses from palm 2/5710 (see Fig. 5.5), six were more susceptible than the trial mean, five significantly so. Corley (1993) and de Franqueville *et al.* (1995) found differences between clones in susceptibility.

In Nigeria, Rajagopalan *et al.* (1978) found that, among 336 progenies, none was immune but 149 showed sufficient tolerance to be considered valuable for breeding; and certain *pisiferas* consistently gave tolerant crosses with a range of *duras*. Prendergast (1963) and Locke and Colhoun (1974) also observed that no progenies appeared to be wholly immune to the disease. However, Rosenquist *et al.* (1990) noted that pure Dumpy Deli *dura* material (see Section 5.1.1.2) appeared to be virtually immune: two families gave 0% and 1% wilt in the nursery test in Cameroon, while one family in Congo had suffered no losses after 10 years in the field, a figure recorded in only two other families out of more than 450 in the programme.

There are reports of resistant material from other countries proving susceptible when imported to Nigeria (Oritsejafor, 1989), but replicated trials were not involved. De Franqueville (1991) tested three strains of *Foe* on 66 different families. There were significant differences between the strains and between the families, but no strain $\times$ family interaction. Mepsted *et al.* (1994) tested three isolates of the fungus from different parts

of Africa, on 14 clones. The isolates differed in aggressiveness, but as in de Franqueville's trial, the clone $\times$ isolate interaction was not significant. These two studies indicate that resistant material selected in one area should remain resistant when transplanted elsewhere.

Symptomless infection: Ho *et al.* (1985) isolated *F. oxysporum* from roots of healthy palms in Malaysia; these strains were apparently non-pathogenic, causing no disease symptoms. Flood *et al.* (1989) showed that one such strain did cause mild wilt symptoms in a susceptible clone, however.

Mepsted *et al.* (1988) found that inoculation of seedling roots with a non-pathogenic isolate could prevent subsequent infection by pathogenic strains. Diabate *et al.* (1992) confirmed this 'cross-protection' effect, and showed that phenolic compounds accumulated in the palm roots after inoculation, whether this was with a pathogenic or a non-pathogenic strain. Susceptibility appears not to be due to a lack of these phenolics, as both resistant and susceptible palms produced them, at similar levels, in response to the non-pathogenic strain of *F. oxysporum*. Presumably, in susceptible palms the fungus normally spreads more rapidly than the build-up of phenolics; preinoculation with the non-pathogenic strain may allow sufficient build-up, in advance of infection, to confer resistance. Both preformed and induced antifungals were extracted from xylem fluids and petiole tissue by Mepsted *et al.* (1995c), with the effect being particularly pronounced in resistant material. Paul (1995) suggested that preformed antifungal compounds were also present in oil palm roots, but the identity of the compounds in roots or petioles was not determined.

Diabate *et al.* (1992) suggested that there might also be competition between pathogenic and non-pathogenic strains in the soil. Flood *et al.* (1989) had previously suggested that competition for an ecological niche may be the reason that *Fusarium* wilt is not present in Malaysia: any strains accidentally introduced from West Africa would face competition from native Malaysian strains.

Plant quarantine: The demonstration that spores of *Foe* can be carried on oil palm seeds (Locke and Colhoun, 1973), and even on the kernel surface inside the shell (Flood *et al.*, 1990), poses potential problems for plant quarantine. Flood *et al.* (1994) showed that the standard 40°C heat treatment used to break dormancy (see Chapter 7) greatly reduced the level of infection, but some viable spores remained. They developed a method of fungicide application involving vacuum infiltration, which eliminated spores, including any within the shell. This treatment should be applied whenever seeds are exported from areas where wilt occurs.

Spores of *F. oxysporum* were also found in batches of freeze-dried pollen used for oil palm breeding, and were shown to be pathogenic (Flood *et al.*, 1990). This contamination can be detected by plating out samples on a *Fusarium*-selective culture medium, but this is laborious if many samples are involved, and a method of decontamination would be useful.

Conclusion: There is no doubt that *Fusarium* wilt can be devastating, and there are instances of plantations in Africa being abandoned or converted to other crops because of the disease. Given the large quantities of seed and pollen exported from Africa in the past, it is surprising that the Far East has remained free of the disease. Perhaps symptomless infection by other strains of *F. oxysporum* gives a degree of cross-protection, but the very strict quarantine measures now enforced by Malaysia and other countries appear sensible (Section 12.1.10). Breeding of resistant material is clearly the best approach to controlling the disease, and as a precaution, breeders in the Far East would be wise to gather information on the performance of their materials in areas where the disease occurs.

12.1.6.3 *Ganoderma* trunk rot or basal stem rot

In the more severely affected areas in the Far East, over 50% of palms may succumb to *Ganoderma*. For many years, *Ganoderma* was regarded as a disease of old palms, of little economic importance because such palms would soon be replanted. In the mid-1950s, however, the disease started to attack much younger palms in the Far East, particularly in areas planted after coconuts or replanted from oil palms (Turner, 1981). In recent years, the disease has been the subject of much research in Malaysia and Indonesia. Most of this work was summarised in Flood *et al.* (2000a), which included a good general review of the current status of the disease (Ariffin *et al.*, 2000). Gurmit (1991) gave a useful review of research up to that date.

Symptoms: The usual first symptom of infection by *Ganoderma* is similar to that of drought conditions: a failure of the young leaves to open, so that a number of fully elongated but unopened 'spears' is seen in the centre of the crown (Turner, 1966a). This indicates that the stem is already extensively damaged, so that water uptake is restricted; it is apparently a direct response to water shortage, so is not necessarily diagnostic for *Ganoderma* (Turner, 1966a). In old palms the lower leaves collapse, hanging vertically downwards from the point of attachment to the trunk (Plate XIVC). This is followed by the drooping of younger leaves, which turn a pale olive

green or yellowish colour and die back from the tip. Later, the base of the stem blackens, gum may be exuded and the distinctive fructifications of *Ganoderma* sp. appear (Plate XIVA). The whole crown of the palm may then fall off, or the trunk may collapse (Plate XIVB).

Bull (1954) described and illustrated the internal symptoms of old palms exhibiting *Ganoderma* trunk rot. In brief, it was found that the peripheral tissues are hard and unaffected by the rot, the black fibres in this zone being normal. Within the stem at the base of the palm the majority of the tissue is yellow-coloured and breaks up easily; mycelium can be found extending through the tissue. Roots are also found to be infected, the cortex being brown and decaying, the stele black. Large numbers of sporophores may be formed, the early ones being small and rounded, the later ones being typical brackets.

Cause: *Ganoderma* species. Early work referred to *G. lucidum*, but that is a temperate species (Steyaert, 1967). The general consensus now appears to be that *G. boninense* is the main species pathogenic to the oil palm, at least in South-east Asia (Moncalvo, 2000). Idris *et al.* (2001) considered that two other species, *G. miniatocinctum* and *G. zonatum*, were also important. Khairudin (1990b) suggested that *G. tornatum* might be involved, but Idris *et al.* regarded that species as a non-pathogenic saprophyte. In this chapter we will follow most authors in referring to the pathogen simply as *Ganoderma*.

Navaratnam (1961) confirmed pathogenicity by inoculating both roots and stems of 40-year-old palms with *Ganoderma* mycelium. More recently, palms at the nursery stage have also been successfully inoculated (Amiruddin, 1993; Sariah *et al.*, 1994; Ariffin *et al.*, 1995b), and the pathogen has been reisolated (Khairudin *et al.*, 1993).

Distribution: In Malaysia, the disease is much more prevalent on low-lying alluvial soils, particularly the coastal clays, than on inland soils, and it is on the former that the most serious attacks on young palms have occurred. Turner (1965a), examining attacks on young palms, showed that incidence on areas where the preceding crop was coconuts was much higher than where planting followed forest or rubber (see also Fig. 12.1). Turner quoted two instances where fields of 15-year-old oil palms after rubber had 4 and 2% *Ganoderma* attack while adjoining areas which followed coconuts had incidences of 39 and 35%. The greatest losses were said to be where old coconut trunks had been buried, to prevent infestation by *Oryctes rhinoceros* (Section 12.2.4.1). Turner (1981) considered oil palm tissue to be a less conducive medium for the fungus than coconut tissue; he quoted survey results showing 24–28% infection in

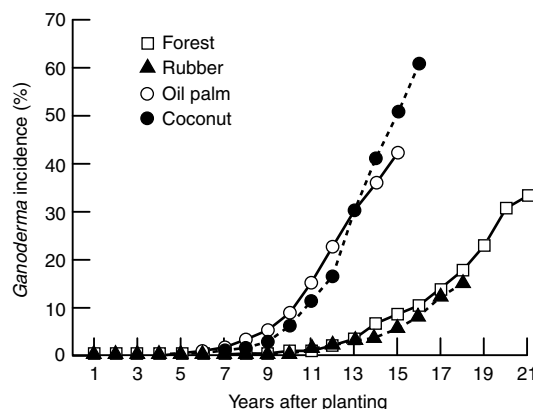


Fig. 12.1 Incidence of *Ganoderma* in oil palm in relation to previous crop. (From data of Gurmit, 1991.)

15-year-old palm to oil palm replants, but 6–81% in oil palms following coconuts (Turner, 1965b). However, Gurmit (1991) quoted a 15-year-old replant with 67% infection, and Fig. 12.1 suggests little difference in the rate of disease development in plantings after oil palm or coconut. On peat soils, a high incidence may be observed whatever the previous crop (Ariffin *et al.*, 1990).

The effect of soil type on disease incidence is not yet understood. Gurmit (1991) suggested that the usually high soil moisture of the coastal soils might favour *Ganoderma* over other, antagonistic soil fungi. According to Swinburne *et al.* (1998), three types of *Ganoderma* can be isolated from oil palms in Malaysia; these were subsequently identified as different species by Idris *et al.* (2001). *Ganoderma boninense* (type A), was significantly more aggressive than type B (actually two species, *G. miniatocinctum* and *G. zonatum*), while *G. tornatum* (type C) appeared to be a non-pathogenic saprophyte. Isolates from coastal soils, usually with a history of previous coconut or oil palm planting, were predominantly *G. boninense*, while those from inland soils were type B. This is consistent with the greater incidence on coastal soils, but it remains unclear whether it is simply coincidental that these types are associated with particular soils. Some live coconut palms were found to contain *G. boninense* as a symptomless endophyte, which could explain the high incidence in plantings following coconuts. Idris *et al.* (2001) speculated that infection by *G. tornatum* might offer some protection against the pathogenic species.

Spread of the disease: If palms in the early stages of the disease are dissected, infection usually appears to have started from the roots. This, and the demonstration that

neighbouring palms were often infected by the same strain of the fungus (Turner, 1965c), led to the assumption that infection under natural conditions is mainly by root contact with an infected palm or other inoculum source. Turner (1981) considered that *Ganoderma* was a weak parasite, and that it needed to develop saprophytically in large masses of dead palm tissue before it had sufficient 'inoculum potential' to infect live plants. More recently, though, Hasan and Turner (1998) showed that even isolated roots from diseased trees could be a sufficient inoculum source.

Seedlings planted very close to *Ganoderma*-infected stumps may show disease symptoms within 1 or 2 years (Hasan and Turner, 1998). These authors showed that poisoned stumps gave higher infection, presumably because they rotted more quickly, and could be invaded by seedling roots more easily. Short (20 cm) stumps gave higher infection rates than 50 cm stumps, perhaps again because they rotted more quickly. Diseased stumps had largely ceased to be sources of infection 2 years after felling. Stumps of healthy palms colonised by *Ganoderma* became sources of infection, and rotted, more slowly than diseased stumps. Hasan and Turner suggested that they therefore remained infectious for longer. They also noted that infected palms may remain apparently healthy for long periods, before the internal damage becomes so severe that external symptoms develop. Ariffin *et al.* (1995a) found, by extraction of trunk samples, that in a 22-year-old planting, between 13 and 17% of palms classified as healthy were actually infected.

Most attempts at control have been based on the assumption that infection is by root contact with an infected palm or other inoculum source. Work with molecular markers has confirmed that this assumption is sometimes correct, as the same genotype was detected in diseased stumps as in seedlings planted close to the stump (Flood *et al.*, 2000b). Some studies on spatial patterns of the disease have shown that diseased palms in some fields tend to be in clumps, which also indicates spread through root contact. However, in other areas the disease appears to be more randomly distributed, as might be expected if spread were by spores (Flood *et al.*, 1998). Recent work with molecular markers (Miller *et al.*, 2000) and mating compatibility studies (Miller *et al.*, 1999; Pilotti and Sanderson, 2001) have indicated that a range of genotypes may exist within quite a small area. Even a single palm may be infected by more than one genotype of the pathogen. This suggests that basidiospores (which are sexually produced and thus genetically variable) may be an important mode of spread.

Bridge *et al.* (2001) used a *Ganoderma*-specific molecular marker to show the presence of *Ganoderma*, in young palms without external symptoms, in the pruned leaf bases. This indicates that the cut leaf bases provide a site for infection by spores. It is possible that the fungus then develops very slowly in palm tissue, and it may be a decade before external symptoms appear, followed by the production of sporophores and a new generation of spores. These may again infect cut leaf bases, this time causing upper stem rot (Section 12.1.6.5).

It seems likely, therefore, that the disease can be spread in two ways. Root contact with an inoculum source, such as old oil palm or coconut trunks, would result in early infection, within a few years after planting. Outbreaks of the disease 15 or 20 years after planting may often be from aerial spores, although slow development of infection that took place more than a decade earlier is a possibility. In PNG it was concluded that spores had so far been the only source of the disease (Pilotti and Sanderson, 2001).

Predisposing factors: The effects of previous crop and of soil type have already been mentioned. The very strong influence of soil type does not appear to have received the attention it merits, but several studies of the effects of fertilisers have been made. Akbar *et al.* (1971) indicated that nitrogen and magnesium may have some role in combating the disease, but more recent trials have given equivocal results. Potassium chloride and urea application have both increased disease incidence in some trials, and decreased it in others (Gurmit, 1991). Tayeb Dolmat and Hamdan (1999) found similar conflicting results with phosphorus and potassium in three trials, two on peat and one on a coastal alluvial soil. Gurmit (1991) noted that high soil salinity and low soil pH appeared to discourage the disease.

Effects on yield: Yield reduction may occur both from death of palms, and from reduced yield in infected but still living palms. Disease losses might be partly compensated for if palms next to gaps gave increased yield, and Turner (1981) stated that there was circumstantial evidence that losses of up to 20% might be compensated for. This may have referred to Prendergast's comments on *Fusarium* wilt (Prendergast, 1957), but other work on that disease suggests that any yield increase is insufficient to compensate for the lost palms (Section 12.1.6.2). More recently, Hasan and Turner (1994) stated that yield compensation ceased at around 10% losses, but again presented no supporting data. The extent to which compensation occurs will depend on the optimal planting density, which varies with soil fertility and with type of planting material (see Section 9.3.3.1). In Sumatra, in plantings from the late 1960s

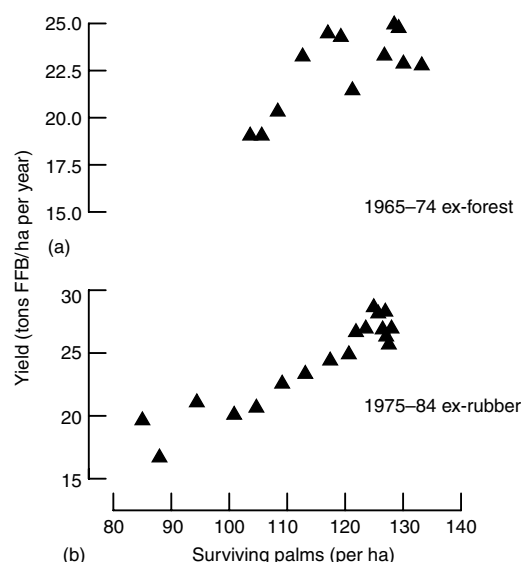


Fig. 12.2 Yield of individual fields in North Sumatra, with different amounts of *Ganoderma* losses. (From London Sumatra, unpubl.)

and early 1970s, there was little decline in yield until the surviving stand had fallen to about 115 palm/ha (Fig. 12.2a), but in more recent plantings, any loss of palms was associated with a loss of yield (Fig. 12.2b).

Khairudin (1995) found that yield of infected palms was reduced by 20–40% in the year before infection was detected. Effects may not always be so large, though: Nazeeb *et al.* (2000) showed that palms with *Ganoderma* yielded between 13 and 21% less than healthy palms at the same age. Gurmit (1991) compared the yield of a field badly affected by *Ganoderma* with that of a less infected field of the same age. The heavily infected field yielded 26% less at 11 years after planting, and 46% less at 15 years, by which time incidence was 67%. It was not stated what proportion of diseased palms had died.

Control at time of replanting: It is generally accepted that incidence of *Ganoderma* increases from one generation of oil palms to the next, but there are few published data to support this contention, the evidence being mainly anecdotal. The 25-year time interval between generations makes reliable comparisons within the same field difficult, and possible genetic differences in susceptibility would further confound comparisons (see *Breeding for resistance*, below).

Table 12.6 shows data from three estates in Indonesia; there appears to be an increase in disease incidence

Table 12.6 *Ganoderma* incidence (% of palms severely affected or dead) in different generations, planted in different blocks at the same time

Estate	Age (years)	Generation			
		1	2	3	4
1	11–15	1.5	7.8	17.9	4.7
2	11–15	–	10.6	10.2	–
	16–20	–	14.9	17.5	–
	21–25	5.1	9.3	17.7	–
	>25	11.4	8.6	–	–
3	11–15	–	11.1	11.1	12.4
	16–20	20.5	20.6	17.8	9.4
	21–25	–	27.6	21.3	–

All blocks were replanted by felling and windrowing; all disease scoring was done in 1999–2000 (de Franqueville, 2000).

over the first three generations in estate 1, and perhaps in estate 2, but not in estate 3. These data are from different fields, recorded at the same time, so could be confounded by the possible effects of soil type already mentioned above. As further evidence against a build-up from one generation to the next, Gurmit (1991) found that fields that ranged from 40 to 60% infection before replanting all had the same level of disease 9 years after replanting. The high incidence in first replants, as shown in Fig. 12.1, suggests that a build-up could occur, but there is little evidence for a further increase after the second replant. Despite this, most control measures are aimed at preventing such a build-up, on the assumption that spread is by root contact with an inoculum source.

The recommended method of reducing *Ganoderma* incidence has been to deal with it at replanting time, by ridding the fields of as much oil palm tissue as possible although, as will be seen, the effectiveness of this is unclear. Mechanical methods of ‘clean clearing’ were outlined by Turner (1981). Stimpson and Rasmussen (1973) gave an account of a system used on the coastal clays of Malaysia which entailed burning or, if this was not possible, cutting up, splitting the boles and windrowing the old oil palms so that they rotted rapidly. The method included prior poisoning of the palms and subsequent root raking and ploughing to bring up and dispose of pieces of palm base and other material that might form a focus for *Ganoderma*. The operations are costly, but have been regarded as essential in coastal areas. In inland areas the incidence of *Ganoderma* is not usually so great, and the emphasis on clean clearing has been less strong.

Table 12.7 Effects of replanting method on *Ganoderma* incidence

Location	Age when surveyed (years)	Disease incidence and deaths (%)			Ref.
		Underplanted	Felled and windrowed	Clean cleared	
Inland (Johore)	17	5.7	5.0	–	1
Inland (Johore)	20	5.5	4.5	–	2
Alluvial (Sabah)	13	23.4	24.2	–	2
Alluvial (Selangor)	15	33.0	17.6	14.0	3
Alluvial (Perak)	15	–	5.4	0.5	4

References: 1: Loh and Rajaratnam (1977); 2: Pamol Plantations Bhd (unpubl.); 3: Khairudin (1990a); 4: Gurmit (1991).

Table 12.8 *Ganoderma* incidence in first and second replants of the same blocks

Block	First replant ^a (2nd generation of palms)		2nd replant ^b (3rd generation of palms)	
	Year planted	<i>Ganoderma</i> (%)	Year planted	<i>Ganoderma</i> (%)
1	1955	4.8 (10 years)	1978	2.8 (10 years)
2	1954	19.5 (12 years)	1976	21.6 (12 years)
3	1955	33.8 (9 years)	1975	32.4 (9 years)
4	1957	2.0 (9 years)	1980	3.5 (9 years)
Mean		15.0		15.1

From Gurmit (1991).

Method: ^aFelled and windrowed, stumps left *in situ*; ^bclean cleared by burning, and raking to remove root and bole tissue

Table 12.7 shows results of a number of comparisons of replanting methods. Disease incidence may be higher after underplanting, but in three out of four comparisons the difference was small. In two trials, the difference between felling and windrowing, and the clean clearing advocated by Turner (1981) and others, was also quite small.

Table 12.8 shows a comparison of first replants (the second generation of palms) with second replants (third generation). The first replant was done by felling and windrowing, without removal of stumps; the second replants of the same blocks were done by clean clearing. The almost identical figures in successive generations can be interpreted in several ways.

- Gurmit (1991) concluded that, because clean clearing had not reduced the incidence, the method needed improving.
- If a large increase from one generation to the next is expected, it could be argued that clean clearing has

been effective in preventing such a build-up (but the evidence for such a build-up is equivocal; see Table 12.6).

- Comparison of clean clearing and windrowing in the same generation shows little advantage for clean clearing (Table 12.7), so the similar incidence in the two generations in Table 12.8 could, alternatively, be interpreted as evidence against a build-up from one generation to the next.

There is a danger of arguing in a circle, but considering all the results available, we suggest that:

- Clean clearing only reduces disease incidence by a small amount, if at all (although what is meant by clean clearing may differ from one organisation to another).
- Incidence does not increase much from one generation to the next, but is more dependent on the strain of *Ganoderma* prevalent in the area, the soil type or some other predisposing factor.

Hasan and Turner (1994) found that very few seedlings planted over 1.5 m away from infected stumps became infected. One approach to replanting severely *Ganoderma*-infected fields could therefore be to plant down the centre of the interlines (4.5 m from the old stumps). It would probably take the roots of the seedling more than 2 years to reach the stumps, by which time, provided they were poisoned, they should have rotted enough as to be no longer infectious. Hasan and Turner (1994) also suggested that a 2-year fallow period should precede replanting, but this would only be acceptable from the financial viewpoint if some other crop could be taken. Gurmit (1991) showed that 1 year under soya beans before replanting had no effect on subsequent disease incidence.

If spores are the main mode of spread, rather than vegetative contact (see *Spread of disease*, above) then clean clearing may make little difference. The important factor would be a source of spores; for instance, infected old palms adjacent to the young palm area.

Nazeeb *et al.* (2000) suggested planting at a higher than normal density when a high incidence of disease is anticipated. They presented yield data up to the seventh year of harvesting to support this suggestion, but by that stage deaths were only 3–7%. Wood (1999) noted that an underplanting with 80% *Ganoderma* losses by 20 years was more profitable, on a discounted cash-flow basis, than clean clearing, even if the latter completely prevented losses. This is because yield many years after the investment has relatively little value in a discounted cash flow.

Other methods of control: Various attempts to control the disease with systemic fungicides have been made. Early work was not successful (Loh, 1977; Jollands, 1983), perhaps because massive lesions may already be

present by the time external symptoms are seen. Ariffin and Idris (1993) found that trunk injection of dazomet had some effect. George *et al.* (1996) obtained a significant reduction in incidence from a combination of carboxin and quintozene, which were more effective than dazomet. The effect was probably to retard development in infected palms, rather than to prevent infection. Effects on yield were not quoted.

Biological control by inoculating lesions with cultures of various micro-organisms was suggested by Varghese *et al.* (1976), and subsequent work was reviewed by Sariah and Zakaria (2000). Soepena *et al.* (2000) described the use of conidia and chlamydospores of *Trichoderma koningii* as a 'biofungicide', but presented no data on its effects. Sariah and Zakaria (2000) studied the effects of *Trichoderma harzianum*, alone and in factorial combination with a mycorrhizal preparation, dried palm oil mill effluent and calcium nitrate, on *Ganoderma* development in inoculated seedlings. Table 12.9 is based on their data, and suggests that $\text{Ca}(\text{NO}_3)_2$, dried effluent and mycorrhizal inoculation may all have had some effect, but *Trichoderma* did not. Yow and Jamaluddin Nasir (2001) claimed that young palms, inoculated with mycorrhiza in the nursery and planted next to diseased stumps, remained free of infection by *Ganoderma* for at least 3 years, whereas uninoculated plants were 'mostly infected'.

Excision of large, discrete lesions ('surgery') has been practised (Turner, 1968), sometimes successfully, but it is expensive, and treated palms may later collapse. Surgery is less likely to work with young palms than with old palms, but it is with young palms, with a long life ahead of them, where the greater benefit would be obtained from a 'cure'. Gurmit (1991) indicated that a back-hoe could be used to do the surgery mechanically, and gave

Table 12.9 Effect of various treatments on *Ganoderma* development in seedlings

Treatment		Foliar symptoms ^a (%)	Roots with lesions (%)	Bole infection (%)
Calcium nitrate	+	18.9	0.0	0.0
	–	41.0	27.6	23.8
Dried palm oil mill effluent	+	22.8	2.1	0.6
	–	37.1	25.5	23.2
Mycorrhiza	+	26.0	3.4	1.1
	–	33.9	24.2	22.8
<i>Trichoderma harzianum</i>	+	28.2	13.9	13.0
	–	31.7	13.8	10.8

Four-month-old seedlings were inoculated with rubber-wood blocks. Data are main effects from a factorial design, from Sariah and Zakaria (2000).

^aPercentage of leaves that were desiccated or chlorotic.

figures for costs, but not for efficacy. Hasan and Turner (1994) obtained some benefit from surgery, in terms of better survival and yield 36 months after treatment.

Removal of diseased palms is probably more widely practised than surgery. Such palms are identified in regular inspection rounds, and removed by poisoning, felling, cutting up the trunk and excavating the bole tissue to hasten decay. Gurmit (1991) presented data which showed that this approach only slightly reduced the rate of spread of the disease. Over a 4-year period, incidence increased from 13 to 50% where infected palms were removed, and from 12 to 57% without removal.

Mounding of the base of diseased palms with soil, after surgery, was suggested by Lim K.H. *et al.* (1995) (Plate XIVD). Numerous new roots developed from the trunk above the point of surgery, with treated palms suffering fewer deaths and some remission of symptoms. Hasan and Turner (1994) found that surgery was unnecessary, mounding alone being just as effective. Ho and Khairudin (1997) found that mounding reduced the death rate from 34% to 2%, over 24 months after treatment. Yields were over 30% higher because of this. Treatment with dazomet as well as mounding gave only a small additional benefit, insufficient to cover the extra cost. By 36 months, only 14% of mounded palms had died, compared with 71% of untreated palms, and yield was over 50% greater as a result (Ho, 1998).

Sanderson and Pilotti (1997; also Sanderson *et al.*, 2000) argued that the disease could be controlled by ensuring that fruiting bodies were never allowed to develop to the point where spores were released. Whether this is a valid approach will depend on the extent to which spread is by spores, rather than root contact. The method needs to be tested.

Breeding for resistance: This is an obvious approach, particularly given its success against *Fusarium* wilt (Section 12.1.6.2). Differences in incidence between West African and Deli material were observed in Indonesia (Akbar *et al.*, 1971), and de Franqueville *et al.* (2001) showed significant differences between families in *Ganoderma* incidence in eight of 12 breeding trials, and between clones in six of seven clone trials. In one trial, for example, incidence in individual families ranged from 12 to 75%, 24 years after planting. An index was calculated, in the same way as for *Fusarium* resistance (Section 12.1.6.2), and showed reasonable consistency for the same parents in different crosses and trials. The development of inoculation methods for plants at the nursery stage should make resistance breeding easier, provided that the processes of infection in seedlings and in mature palms are similar. Amiruddin (1993) used several different *in vitro* inoculation methods to compare

three clones, and observed consistent differences among the clones in susceptibility, but Ariffin *et al.* (1995b) found no differences among 20 progenies in a nursery inoculation trial.

Conclusion: *Ganoderma* has been a serious problem in some areas in Malaysia and Indonesia for 40 years. Despite recent collaborative research (Flood *et al.*, 2000a), our knowledge of the disease still depends heavily on anecdotal evidence, and several aspects remain surprisingly obscure. A great deal has been invested in clean clearing at replanting time, but there is little evidence that this has had much effect. Nor is there convincing evidence that the problem is getting worse; it still needs to be confirmed that the disease increases from one palm generation to the next. An attempt to collate the extensive data that must be available in plantation records, in relation both to palm generation and to replanting methods, might be very informative (Wood, 1999). More research on predisposing factors also appears to be needed.

Mounding of diseased palms, perhaps combined with fungicide treatment, can delay death and improve yield. This appears to be preferable to the removal of diseased palms, which does little to prevent disease development. Systematic removal of all fruiting bodies, to prevent spread by spores, has yet to be tested as a means of control. It appears to us that, in the longer term, the best approach to controlling the disease in areas where it is prevalent may be to develop tolerant material, using nursery inoculation for screening, in much the same way as has been done for *Fusarium* wilt.

12.1.6.4 *Marchitez sorpresiva*, sudden wither or 'hartrot'

Distribution: This disease has been serious on plantations in Colombia, Ecuador and Peru (Plate XID). In Surinam the disease has been described as 'hartrot' (van Slobbe *et al.*, 1978), and a similar condition has occurred in Bahia, Brazil.

Symptoms: The disease is characterised by a sudden rotting of all developing bunches, a reddish discoloration of the top of the petioles and rapid drying out of the leaves from the oldest ones upwards. This drying out is preceded by the appearance of reddish-brown streaks at the ends and centres of the lowest leaflets. The leaf then becomes successively pale green (as in nitrogen deficiency), yellow, reddish-brown and ash-grey (Genty, 1981). The palm dies in 2–3 weeks and as soon as the external symptoms appear the root system will be found to have rotted and to a large extent dried out. Similar symptoms, though proceeding at a slower rate,

are sometimes seen, and in Colombia this has been referred to as 'marchitez progresiva'. However, there may be confusion with fatal yellowing (Corrado, 1970). In the typical marchitez symptoms, the spear is initially unaffected. The root rot is cortical. The cortex decomposes in wet weather, but in the dry season tends to become necrotic and to detach itself from the stele. The rot starts to develop from the extremities and moves towards the trunk and towards the lower roots. The trunk itself usually remains healthy, but cases are reported where the base is rotted sufficiently to form a cavity (Martin, 1970; van den Hove, 1971). Palms have been attacked by marchitez from the age of 1 year.

Cause: Evidence has been accumulating that the cause is infection by a protozoan flagellate, *Phytomonas staheli*. These have been found in several countries in association with the disease, in the phloem of roots, meristem zone, spear base and inflorescence stalks (Dollet *et al.*, 1977; Dollet and Lopez, 1978; Dzido *et al.*, 1978), and are also present in certain weed species (Dollet, 1982).

A connection between infection and insect attack has been suggested. Lopez *et al.* (1975) considered that the root miner, *Sagilassa valida* (Genty, 1973) (Section 12.2.7.1) might be a carrier, although the disease is often absent in areas where the miner is present. In Colombia, where the disease devastated an area of palms growing in a heavy stand of *Panicum maximum*, the bug *Myndus crudus* (*Haplaxius pallidus*) was found on palm leaves while the nymphs were present on the roots of *P. maximum*. The use of herbicides and insecticides reduced the incidence of marchitez (Mena Tascon *et al.*, 1975), while inoculation experiments (Mena Tascon and Martinez-Lopez, 1977) also suggested that *M. crudus* might be playing a part in the transfer of the disease.

Desmier de Chenon (1984) and Perthuis *et al.* (1985) claimed that the bug *Lincus lethifer*, which lives in the axils of the leaves (Dollet *et al.*, 1977), was the vector of the flagellate. Symptoms of the disease developed within a few months of the bug being released onto young palms, in the first instance at sites far from any cases of the disease, and in the second on a caged palm surrounded by other, healthy palms. It has also been shown that *L. lethifer* and another species, *L. tumidifrons*, can transmit the flagellates to coconut palms, where they cause hartrot (IRHO, 1992b).

Control: In view of the uncertainty of diagnosis it is difficult to recommend definite control measures. On the grounds that *Sagilassa valida* was likely to be playing a part in the transmission of the disease, applications of insecticide around the base of the palms have been used to suppress the insect, and were strongly

recommended in Colombia, Ecuador and Peru (Lopez *et al.*, 1975; Genty, 1977). As noted above, it now appears that *Lincus* spp., not *S. valida*, are probably involved, and Gomez *et al.* (1996) indicated that a combination of insecticide and herbicide (to eliminate alternate host plants for *Lincus*) has proved useful.

Cases of marchitez in *E. oleifera* × *E. guineensis* hybrids have not been recorded until recently, so it is possible that the planting of hybrids may be a method of avoiding the disease, although, as with fatal yellowing (Section 12.1.7.2), we doubt whether such a policy can be justified, because of the poor oil yield of hybrids. In Surinam, however, some hybrids have suffered from 'hartrot', although wild *E. oleifera* palms have not been observed with the disease (Alexander and Kastelein, 1983). Certain *E. guineensis* palms on a plantation devastated by this disease remained healthy (Hartley, 1988), so it may therefore be possible to select resistant progenies within the species.

12.1.6.5 Upper stem rot

Thompson (1937) described a lethal trunk rot that was serious only on deep peat and inland valley soils. The disease has appeared on other soils in both Malaysia and Indonesia, but is usually sporadic and not of major importance.

Symptoms: Typically, the lower leaves first become yellow and this symptom gradually extends to the middle leaves and then to the spear. It is evident that spore infection of leaf bases takes place and that from these the fungus gains entry to the peripheral tissues of the stem. The brown decay appears to proceed slowly inwards from the leaf bases and in many cases a typical collapse of the stem at one point occurs, this usually following high winds (Plate XVB). The rot spreads upwards and downwards in the stem, eventually killing the palm by invading the crown. Two forms of fruiting bodies (normal and resupinate) appear, but only on palms where the leaf bases are extensively decayed. These are small, greyish-brown bodies with velvet-brown margins and are inconspicuous among the leaf bases. The disease is confined to the stem and does not enter the roots.

Cause and distribution: *Phellinus (Fomes) noxius*; perhaps also *Ganoderma*. Thompson (1937) described the disease, but little work was done on it until Navaratnam and Chee (1965) and Turner (1969, 1981) gave accounts of its symptoms, incidence and control. The pathogenicity of *P. noxius* was proven by inoculation experiments. *Ganoderma* (Section 12.1.6.3) is also often found in association with upper stem rot, perhaps usually as a secondary infection, but Turner (1981) noted the

possibility that this fungus might sometimes cause the disease, and isolations made in Sumatra have confirmed the presence of *Ganoderma* in all cases of upper stem rot examined (J. Flood, pers. comm., 2001).

Control: As there is usually much penetration of the stem by the time sporophores appear, it is desirable to detect the disease at an earlier stage. This can be done on palms of 10 years or older by striking the leaf bases with a wooden pole to detect the dull sound of an infected base. Incidence is insufficient to justify surveying palms below 10 years old. When the diseased leaf bases are cut away the extent of the infection can be explored. The lesion is excised from the stem with a harvesting chisel and the cut surfaces are treated with a preservative (Turner, 1969). Coal tar has been reported to give the best overall results. Treated palms give as high a yield as untreated palms, so the measures are considered worthwhile wherever incidence is likely to be significant.

In a fertiliser experiment containing different progenies, there was evidence first that fertilisers containing potassium reduced incidence, and secondly that progeny differences in susceptibility existed (Navaratnam and Chee, 1965).

12.1.6.6 Red ring disease

Distribution: Red ring is confined to South America, where it has been found in oil palms in Venezuela, Surinam, Brazil and Colombia, where the similar disease of coconuts is prevalent. It has been studied on an estate in Brazil where it did considerable damage (Schuiling and Dinther, 1982). In unprotected areas, incidence can rapidly become high; Malaguti (1953) cited a group of 100 palms showing only 16 doubtful cases in January which by August had 22 deaths, nine doubtful or affected cases and only 69 palms remaining healthy.

Symptoms: The symptoms of this disease have been described by Malaguti (1953). The centre of the crown takes on a dwarfed appearance and the newly opened leaves become bundled together into an erect, compact mass, the leaflets being corrugated, twisted and sometimes adhering to the rachis. Gum is exuded. Later, this crown of leaves turns slowly yellow and dries out, the rachis being a light brown colour with yellow spots. One or two of the intermediate leaves become bronzed and after 2–5 months all of the leaves gradually become yellow or bronzed, although remaining erect. Developing bunches rot and inflorescences fail to set fruit.

The most striking interior symptom is the brown cylindrical ring found in the trunk, 7–8 cm from the periphery and 1–2 cm broad (the ring is red in coconut, hence the name). This ring is most distinct towards the

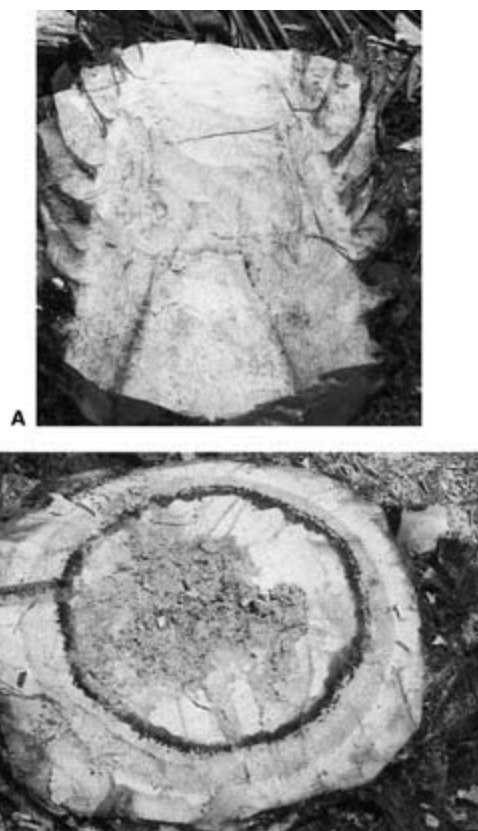


Plate 12.3 Longitudinal (A) and transverse (B) sections of an oil palm suffering from 'red ring' in Venezuela.

base of the palm (Plate 12.3), but the infection proceeds upwards into the petioles and rachis of the leaves in the crown in which, on cross-sectioning, necrotic areas or spots can be found. This infection does not, however, invade the tissues of the stem apex or surrounding very young leaves.

Cause and spread: The coconut nematode, *Rhadinaphelenchus* (formerly *Bursaphelenchus* or *Aphelenchus*) *cocophilus*, seems first to have been recorded on oil palms by Freeman (1925) in Trinidad. Proof that the nematode was the cause of red ring was obtained by Malaguti (1953), who did tests with inoculum from both the oil palm and the coconut. The disease appeared 2–10 months after inoculation.

Giblin-Davis *et al.* (1989) described the nematode as an obligate plant parasite, which is only able to reproduce in palm tissue, but can also parasitise the weevil *Rhynchophorus palmarum*, which thus acts as an important vector for the palm disease. Gerber and Giblin-Davis (1990) found that 90% of the weevils emerging from

infected palms carried the nematode either internally or externally. According to Gomez *et al.* (1996), *Metamasius hemipterus* is the main vector in Colombia, but Chinchilla *et al.* (1996) considered that the latter species was not a vector in Costa Rica, and Schuiling and Dinther (1982) found that *M. hemipterus* did not carry the nematode in Brazil. Warwick and Bezerra (1992) showed that transmission in coconuts could also occur by root contact, so this possibility cannot be ruled out for oil palm.

In Brazil, Schuiling and Dinther (1982) found both the nematode and *R. palmarum* on wild *Oenocarpus distichus* palms, and suggested that these may form a reservoir for infection of plantation palms.

Control: Incidence on an affected estate in Venezuela was greatly reduced by the taking of regular sanitary measures (Hartley, 1988, p. 629). Any diseased palm was poisoned, felled and burnt. The whole estate was inspected every 2 months for diseased palms. Most important was the protection of the palm against the type of wounding that provides sites for *R. palmarum* to lay its eggs. A high incidence of red ring in Brazil was preceded by very close leaf pruning which had resulted in wounding of the trunk (Schuiling and Dinther, 1982); care must be taken when removing leaves to make a clean cut sufficiently far up the petiole to avoid this. Circle-weeding with herbicides instead of with hand tools may also help to prevent wounding. Regular disinfection of tools has been suggested, together with treatment of the cut leaf and bunch-stalk surfaces, but provided that wounding is avoided, it is doubtful whether such precautions are necessary.

Oehlschlager *et al.* (1993) described a pheromone-based trapping method for the vector, *R. palmarum*. Chinchilla *et al.* (1995) showed that after a year of trapping, red ring incidence was reduced by two-thirds. Chinchilla *et al.* (1996) showed that pheromone trapping could also be used against *M. hemipterus*. Biological control of *R. palmarum* has been proposed (Moura *et al.*, 1993).

12.1.7 Diseases of the bud or stem apex

Under this heading are grouped diseases occurring in the emerging spear and younger leaves inside the crown. Such diseases normally move towards the growing point through the enclosed developing leaves of the 'cabbage', and when they reach it the palm is killed. Bud and spear rots have occurred widely in all three continents and provide, perhaps, the most difficult problems of oil palm pathology. Investigation is difficult owing to the position of the transition zone, often in the heart of the palm, the rapid entry of secondary organisms into any rot within the cabbage and the multiplicity of confusing symptoms, some of which may be similar to those of deficiencies or genetic abnormalities.

Turner (1981) suggested that the term 'spear rot' should apply to diseases in which the primary rotting affects the spear, while 'bud rot' should be used only for diseases first destroying the unemerged leaves and the hidden base of the spear and also, usually, the apical meristem. The latter diseases are usually fatal, the former frequently not.



Plate 12.4 Young palm suffering from spear rot, with no central leaves, Panama.

12.1.7.1 Spear rot–little leaf disease

Distribution: This disease, previously called bud rot–little leaf, caused serious losses in the oil palm areas of southern Congo, where deaths exceeding 30% were recorded. Elsewhere in West Africa and in Asia cases rarely exceed a few per cent and are often confined to certain progenies; deaths occur but are rare.

Symptoms: The first sign of attack is a wet, brown rot on the lower part of the unopened spear leaf. Duff (1963) described how in very mild cases only the leaflets may be affected; the leaflet rot is passed from spear to spear until either it develops further or the palm grows out of the attack. Normally, however, the rachis becomes infected and the spear collapses and hangs down; it is not uncommon to find a spear leaf, in which the infected portion has rotted away altogether, lying on the ground where it has fallen. The spear rot grows downwards and may become a bud rot, but it is only if this reaches the growing point that the palm dies. In other cases, the first leaves to emerge after the spear rot are stumps consisting of the malformed basal portion of the rachis. Subsequent ‘little leaves’ are very short with a few corrugated shortened leaflets, but each successive leaf will be longer, and the leaflets less abnormal, until fully normal leaves are again produced. Little leaf is therefore a recovery symptom and does not precede rotting. Very similar symptoms may occur after damage by insects such as *Oryctes* (Section 12.2.4.1).

Cause: Many causes have been assigned to the ‘little leaf’ symptom; for the early history of investigations, the paper by Bull and Robertson (1959) should be consulted. One common cause is boron deficiency (Ferwerda, 1954) (see Section 11.4.1), but this is not preceded by spear rot. Robertson (1960), working in Nigeria on palms of a susceptible progeny having regular cycles of infection, showed that spear rot–little leaf disease was an active pathogen, since the appearance of little leaves and bud rot could be prevented by cutting off the spear below the rotted portion. Although prior insect attack is often suspected, it is not known for certain how spear infection takes place.

A bacterium of the genus *Erwinia*, similar to *E. lathyri*, was consistently isolated in Congo by Duff (1963) from young lesions and from tissue in advance of visible rotting, and inoculation experiments showed that spear rot–little leaf symptoms could be induced by it. Susceptibility seems to be genetic, physiological and seasonal. In a field in Nigeria the disease was confined to one progeny. Genetic differences were also found in Congo, where there was an association between rate of

growth and disease incidence. The former was judged by the rate of elongation of spears and in susceptible palms the elongation rate fell below normal levels 2 or 3 weeks before an attack of the disease. It was believed that these circumstances, encountered in ‘unhealthy’ palms, allowed susceptible tissues to be exposed to infection for longer periods than normal. Palms in which the growth rate was artificially reduced by root or leaf cutting showed greater than normal susceptibility. In some instances there has been high incidence at either the beginning or end of the rains (Turner, 1981).

Kochu Babu (1988) described a similar disease from Kerala, southern India, where frequency of the disease increased with proximity to coconuts affected by root wilt or *Areca* palms affected by yellow leaf disease (Kochu Babu and Ramachandran, 1993). Mycoplasma-like organisms have been found in tissues of palms with these diseases, but were not found in oil palms with spear rot (Kochu Babu, 1988). Spear and bud rots in America have different and varying symptoms (Section 12.1.7.2).

Control: Duff (1963) provided growth and health records showing that the more vigorous progenies suffered less from the disease, and he inferred from this that anything interfering with vigorous growth increased susceptibility. While, therefore, the disease is not likely to be serious enough for control measures to be taken in areas where growth conditions, particularly those of water and nutrient supply, are good, in marginal areas the planting of particularly vigorous progenies might be considered (Hartley, 1988).

12.1.7.2 Fatal yellowing or lethal bud rot (*podrición de cogollo, amarelecimento fatal*)

A bud rot with variable symptoms, but not usually including the typical ‘little leaf’ progression, has caused serious damage on plantations in Central and South America. Some plantations have been totally devastated, while others have suffered serious losses with many palms remaining in a moribund, unproductive condition for long periods. There has been extensive research on this disease in recent years, much of it reviewed by Gomez *et al.* (2000). Turner (1981) called the disease fatal yellowing, from one of the characteristic symptoms. However, symptoms differ quite considerably between different areas, and the disease is not always fatal. There appear to be both ‘acute’ and ‘chronic’ forms, which may be different manifestations of the same disease, as with *Fusarium* wilt (see above), but it appears more likely that more than one disease is being described under one name (IRHO, 1992b; de Franqueville, 2001) (see below, under *Cause*).

Symptoms: In the Llanos Orientales region of Colombia typical symptoms were described by Gomez *et al.* (2000) as dry or wet spear rot, accompanied by yellowing of young fronds (Plate XVD) appearing during wet periods, but disappearing during the dry season. The rot spreads downwards towards the growing point, but affected palms usually recover. Turner's description (1970) of the symptoms in La Arenosa plantation in northern Colombia was quite similar, but it appears that the disease killed many palms when the rot spread to the growing point. Turner noted a tendency for four to six young spear leaves to remain unopened and stuck together, as a 'baton', but he was not convinced that this was a valid disease symptom. When this symptom was seen, spear rot was said to follow within 10–30 days. The rot spread downwards, and within 1–9 weeks the spear collapsed, the rot reached the growing point and the palms died (Plate 12.4). This seems to be the typical 'acute' form of the disease.

As already noted, the symptoms and the severity of the disease appear to vary considerably from one country to another. De Franqueville (2001) described the disease as having two phases: in the first phase, which may last for up to 12 years, increase is more or less linear, but then as foci start to develop, it moves into a phase of exponential increase. Table 12.10 lists the symptoms described by various authors. The main differences are in the extent of chlorosis, the speed with which the spear rot develops, and whether or not the rot reaches the growing point, causing death. The disease appears to take its most acute form in Ecuador, while the most extreme chronic form is that seen in Brazil (Parastate) (Plate XVC) and Surinam. De Franqueville (2001) noted that more acute symptoms were seen elsewhere in Brazil. Swinburne (1990, 1993) reviewed symptoms in Brazil, Ecuador and Colombia; he noted that chlorosis is a common response to stress in many plants, and is poor evidence for a common cause. The symptoms that he described for Brazil are similar to those for leaf mottle (Section 12.1.5.4); they are also similar to those described for iron deficiency by Setyobudi *et al.* (1998).

Cause: A wide range of causative agents has been suggested, including insects, fungi, bacteria and viroids. It should be noted that, as symptoms vary from country to country, it is not certain that they are of the same disease or have the same cause. Nieto (1992) believed that the Colombian and Brazilian forms were different diseases, as did Swinburne (1990, 1993). No direct evidence of infectious spread has been found, but in Surinam, van de Lande (1993a) and van de Lande and Zadoks (1999) found a tendency for the disease to spread with the prevailing wind. Downwind

spread was also noted in Brazil (Swinburne, 1990, 1993), but this observation was contradicted by Bergami Filho *et al.* (1998) and Laranjeira *et al.* (1998), who found, in later results from the same plantation as Swinburne, no preferential direction of spread, and a tendency for diseased palms to occur near water courses. These authors concluded that the disorder had an abiotic cause.

Ochoa and Bustamante (1974) isolated *F. moniliforme* var. *subglutinans* from diseased palms, and inoculation of palms grown in high humidity and low light intensity caused spear rot. This fungus was said to cause diseases with similar symptoms in sugar cane, maize, sorghum and *Musa* spp. However, Turner (1981) considered that symptoms were unlike those normally associated with *Fusarium* attack.

Recently, it has been reported from Colombia that *Thielaviopsis paradoxa* causes the disease; drying and necrosis of the central leaves was induced by inoculation of seedlings (Gomez *et al.*, 2000). These authors imply that *T. paradoxa* was also isolated from diseased palms in Ecuador and Brazil, with different isolates stated to have 'different pathogenicities' and with significant variation in the reaction of seedlings to different isolates. However, de Franqueville (2001) stated that *T. paradoxa* was very rarely found in Brazil or Ecuador. It is possible that the chronic form of the disease seen in Colombia is caused by *T. paradoxa*, but that the acute form elsewhere has some other cause. It should be noted that the perfect stage of *T. paradoxa*, *Ceratocystis paradoxa*, is associated with dry basal rot (Section 12.1.6.1), which has quite different symptoms. The fungus is described by Turner (1981) as 'one of the most common fungi recorded on the oil palm throughout the world', and is not normally pathogenic. If this is the pathogen, therefore, it is not yet clear what renders palms susceptible to it in Latin America, but not elsewhere.

Other fungi that have been isolated from diseased spears include *Fusarium oxysporum* and *Botryodiplodia* sp. in Colombia and *F. solani* and *Sclerophoma* sp. in Ecuador. Invasion of bud tissue by many species of bacteria follows the basal spear rot. Pathogenicity of these organisms has not been demonstrated, but de Franqueville (2001) speculated that a joint infection by a fungus and a bacterium may be involved. In Brazil, a viroid was suggested as the cause (Singh *et al.*, 1988), but viroid-like RNA was found in both diseased and healthy palms (Beuther *et al.*, 1992).

Insects have also been associated with the disease. In Colombia a *Cephaloleia* sp. was found to induce symptoms similar to those of the early stages of the disease, and Urueta (1975) studied a range of other insects in diseased material. In Ecuador, Dzido *et al.* (1978)

Table 12.10 Symptoms of fatal yellowing in different countries

Symptoms	Colombia La Arenosa	Colombia Llanos Orientales	Ecuador	Surinam	Brazil	Panama	Nicaragua	Costa Rica
'Baton' effect	Often	No	No	–	No	–	–	–
Chlorosis (no. of leaves)	A few	A few, mild	A few	Few initially, later many	Many	Often none	Some	A few
Spear break or collapse	Yes	Yes	Yes	Yes	Yes	–	–	Yes
Spear rot	Yes	Yes	Rapid	Usually	Eventually	Yes	Yes	Often
Leaves reduced in size	No	No	No	–	Yes	–	Yes	No
Spread to meristem	Rapid	Rare	Rapid	Slow	Slow	Slow	Slow	Rare
Bunch rot	No	No	–	No	Sometimes	No	–	No
Root rot	–	–	No	No	Yes	–	–	Malformation
Recovery or remission	Rare	Yes	No	Yes	Yes	Yes	Yes	Yes
Death	Yes	Rare	Yes	Yes	Eventually	–	Yes	Rare
Time from 1st symptom to death	4–5 months	Rare	1–2 months	1–2 years	1–3 years	–	–	Rare

Based on Turner (1970, 1981), van de Lande (1993b), van Slobbe (1986), Swinburne (1990, 1993), Chinchilla and Duran (1999) and personal observations (R.H.V. Corley).

–: no information available.

found larvae of *Alurnus humeralis* (Coleoptera: Chrysomelidae: Hispinae) and several other insects on diseased palms, but no definite connection between these insects and the disease has been established. Intensive efforts to identify vectors for the disease in Ecuador and Brazil have been unsuccessful (IRHO, 1992b; de Franqueville, 2001).

Wood (quoted by Swinburne, 1990, 1993) found that application of several different herbicides to the roots could cause symptoms similar to fatal yellowing. This suggests the possibility that, if diseased palms were poisoned as a control measure, transmission of herbicide to healthy neighbours may occur through root contact. This could be a contributory factor to the rapid spread of disease sometimes observed, as the neighbours would then show symptoms, and would be poisoned in turn. Swinburne noted that this could not be the only cause, as fatal yellowing has been observed on smallholdings never treated with herbicides.

Predisposing factors: Whatever the pathogen, it is clear that there must be predisposing factors for the disease to develop. It has frequently been associated with poor drainage; Alvarado *et al.* (1997) found, in nursery trials with a susceptible progeny, that poor drainage led to significantly higher spear rot incidence than 'excessive drainage'. However, drainage improvements did not slow the spread of disease in Ecuador (de Franqueville, 2001). Compacted soils and unbalanced nutrition have been mentioned as predisposing factors: in northern Colombia, areas with compacted ex-pasture soils suffered the highest casualties. A low potassium/magnesium ratio was also suspected, but corrective manuring did not stop the disease spreading in La Arenosa (Hartley, 1965; Turner, 1981). Munevar *et al.* (2001) recorded higher incidence of the disease on soils with high clay content, on compacted soils and on poorly drained soils, and they found a much slower rate of spread of the disease where drainage was improved. De Franqueville (2001) mentioned several studies on trace elements, but noted that differences between diseased and healthy palms may be effects, not causes. In Colombia, leaf levels of phosphorus, copper and particularly potassium were lower in infected than in healthy palms, while calcium and magnesium levels were higher (Munevar *et al.*, 2001).

Chinchilla and Duran (1999) described a 'dry spear rot' in Costa Rica, which appears similar to the milder forms of fatal yellowing in Colombia. They noted particularly that the root systems of both healthy and diseased palms in affected areas were poorly developed, with many malformations (corky texture, abnormal branching), and that in affected palms vegetative vigour

was reduced before symptoms developed. In some areas recovery occurred after drainage and other management aspects were improved (see *Control*, below). They concluded that any pathogens were a secondary problem, and that the disorder resulted from stress caused by poor soil aeration, in areas with a high water table and inadequate drainage, or suffering from soil compaction or with shallow soil overlying gravel. However, de Franqueville (2001) quoted several studies in other countries showing that the root system of affected palms was normal and healthy.

Effects on yield: Very heavy losses of palms have occurred on certain plantations in Colombia, Ecuador and Brazil, with severe effects on yield. The heaviest losses have often been associated either with surgery to remove rotting spear tissue, which may expose the growing point and increase subsequent damage, or with deliberate destruction of diseased palms, and sometimes of healthy palms surrounding diseased points, in an effort to prevent the disease spreading. It appears not always to have been appreciated that, if 14% of palms show symptoms (whether fatal or not), and those palms and their six immediate neighbours are destroyed, close to 100% mortality will result. Van Slobbe (1988) noted that 46,000 palms had been 'lost to the disease' on one plantation in Brazil, but also that 'all diseased palms have been eliminated within a month after detection'. De Franqueville (2001) later reported that this plantation had been abandoned because of disease losses. Van de Lande (1993b) recommended that even recovering palms should be destroyed in Surinam, as it was not certain that they were not still infectious.

In Colombia and Costa Rica, affected palms usually recover if they are left untouched (Chinchilla and Duran, 1999; Gomez *et al.*, 2000). Santacruz *et al.* (2000) stated that 80–90% of palms recovered within 1.5–3 years. If palms are left to recover naturally, then yield also recovers, although this may take some time. Chinchilla and Duran (1999) stated that 2 years after the first symptoms had been seen, yields were still below those expected from palms of that age. Santacruz *et al.* (2000) found that yields of fruit were depressed by 30–40% in the first 2 years; oil/bunch was also slightly depressed. Acevedo *et al.* (2000) showed that both FFB yield and oil/bunch were reduced, and oil yield was halved in the worst affected palms.

Control: Speculative prophylactic applications of mixed fungicides and insecticides have not been successful (e.g. Gomez *et al.*, 2000). Surgical removal of rotting spear tissues was widely practised in Colombia at one stage, but Santacruz *et al.* (2000) stated that recovery was just as good if no surgery was done. Destruction

of infected or suspect palms has been widely practised but, as noted above, this has probably contributed more to the problem than to control.

Chinchilla and Duran (1999) indicated that the disorder could be prevented by improving drainage, mulching with composted empty bunches, and paying particular attention to potassium and phosphate nutrition. Affected blocks more than 20 years old were replanted, after subsoiling to rectify soil compaction. In Colombia, the problem has been greatly reduced where drainage was improved (Munevar *et al.*, 2001). Deep ploughing, to improve soil aeration, and fertiliser application to lower the (Ca + Mg)/K ratio, also reduced disease incidence (Acosta *et al.*, 2002).

Breeding for resistance: It is possible that there may be resistant lines within *E. guineensis*: there are several reports of differences between progenies in disease incidence (e.g. Santacruz *et al.*, 2000), with Deli × Avros material apparently being more susceptible than other origins in Colombia. In Ecuador, de Franqueville (2001) reported differences in rate of disease development between crosses of Deli × La Mé origin. Ayala (1999) described a method for testing the susceptibility of individual palms by inoculation of petiole sections with *T. paradoxa*.

On La Arenosa plantation in Colombia several plots of *E. oleifera* × *E. guineensis* hybrids survived while large numbers of the surrounding *E. guineensis* palms died. Similar observations have been made elsewhere (IRHO, 1992b). In areas subject to fatal yellowing, the planting of this hybrid has been regarded as a possible method of combating the disease, and large parts of La Arenosa were replanted with hybrids (Turner, 1981). However, oil yield of these hybrids is generally poor, because of low oil/bunch (although they may have other advantages; see Section 5.5.1.6 for further discussion).

Conclusion: In Ecuador and parts of Colombia, this complex of symptoms is undoubtedly a serious problem, but in many areas it seems that its importance has been exaggerated, and losses have been exacerbated by the measures taken to 'control' the 'disease'. Good agronomic management appears to be the answer in most places. Planting of interspecific hybrids is unlikely to be justified, given the poor oil yield of such material, and we think that other reasons besides resistance to this disease are needed to justify the efforts put into breeding of such hybrids.

12.1.8 Diseases of the bunches and fruit

The occasional bunch and fruit rots that are encountered have not been extensively studied. Bunch-end rot has been associated with the Deli palm, particularly in

Malaysia (Thompson, 1934). Where neither lack of pollen nor insect attack is implicated, both this condition and complete bunch failure have been attributed to 'over-bearing' (Turner and Bull, 1967): the number of bunches is thought to be more than can be sustained by the palm's processes of assimilation. As discussed in Section 4.3.6, however, the evidence for this is not convincing.

A bunch stalk rot has been connected with an unexplained condition in West Africa known as leaf base wilt (Bull, 1954). The leaves bend down towards the ground and the stalks of bunches in the leaf axils also bend and may then begin to rot. The disease seems to be of purely mechanical origin and provided the rot is not so extensive that the bunch falls, the majority of fruit will develop. The small splits that appear in the stalk are invaded by a variety of saprophytic bacteria and fungi.

Marasmius palmivorus is common as a saprophyte on the cut leaf bases and on the decaying debris between these and the trunk. It appears that, under moist conditions in the Far East, sufficient inoculum potential may sometimes build up for healthy bunches to be invaded (Turner, 1965d). For a full discussion of the factors involved in the spread of the disease, Turner (1981) should be consulted. The obvious means of control is to reduce, through sanitary measures, the medium on which the fungus grows on the palm. Rotting bunches should also be removed. Prophylactic spraying against *Marasmius* is not generally recommended, but Turner (1981) considered that on acid sulfate soils in Malaysia spraying may be economically justified.

12.1.9 Other abnormal conditions

The oil palm is subject to many abnormal conditions of growth and development, the causes of which are not known. Usually, although not always, these abnormalities are encountered where conditions are in some way adverse: impoverished sandy soils, long dry seasons, excessively wet conditions or intermittent waterlogging, grass competition, pockets of unusual soils, etc. In the more severe conditions bunch yield is usually negligible (Courtois, 1968). Only a few are mentioned here.

The term plant failure was used by Wardlaw for palms that almost ceased to grow. The rate of root and spear production, and the number of green leaves, decreases and the leaves that remain are erect and crowded. This, in turn, leads to a tapering of the trunk and progressive deterioration of the leaves, which are subject to various kinds of chloroses, dry out prematurely and become brittle. There has been much speculation on the reasons for such palms being found dotted about among normal ones. The condition rarely occurs

in Asia. In Africa it is either considered to be of genetic origin, or may be associated with severe potassium and magnesium deficiency, or where soil depth varies sharply from point to point.

A condition known as choke, or dwarfed crown, has been encountered in fields in America suffering from red ring disease (Section 12.1.6.6), but does not appear to have the same cause (Malaguti, 1953). It has been referred to as *hoja pequena* (little leaf), but the term 'little leaf' should be reserved for the recovery symptom of spear rot–little leaf. In this condition all the leaves are smaller than normal, green, erect, bunched together and twisted with varying amounts of atrophy or corrugation of the leaflets. A sudden recovery from the condition is frequent, a tall cluster of normal new leaves being produced in the centre of the deformed ones, giving the palm a two-tier appearance. This type of deformity is not unknown elsewhere, and the term 'choke' has been used in Malaysia to describe a similar condition.

The oil palm is occasionally killed by lightning strike. Young palms can collapse rapidly and wither, but a sublethal condition known previously as rachis internal browning is now also believed to be caused by lightning (Turner, 1981). In older palms the trunk base is often charred. Lightning strike can usually be distinguished from other causes of death because surrounding palms show scorching on the side facing towards the strike.

Oil palms are quite tolerant of short-term flooding, and have been successfully established in river flood plains. However, if young palms are flooded to a level above the leaf axils, so that silt is deposited in the axils, extensive inflorescence abortion, and sometimes death of the palm, may follow. The risk diminishes as the palms grow taller, but significant losses have sometimes occurred in young plantations (Teoh *et al.*, 2001).

12.1.10 Plant quarantine

The existence of serious diseases in some areas but not others justifies strict plant quarantine measures. Fungal spores are the most likely contaminant, but nematodes (unidentified, but in this case apparently harmless) have been found on germinated seeds (Kushairi and Rajanaidu, 2000). There are already examples of diseases spreading: as noted in Section 12.1.6.2, *Fusarium* wilt was spread from Africa to South America with oil palm seeds. The precautions adopted in Malaysia were described by Kang (1986), and included prohibitions on import of seed or pollen from areas where diseases of unknown aetiology occur, prohibition of import of

secondary hosts or insect vectors of disease, and limits on the quantities of seed imported. Precautions must start in the country of origin, with inspection of parents palms for disease and thorough cleaning of materials. Where possible, seed and pollen should be screened for spores of important fungal diseases at an intermediate quarantine centre, between the country of origin and the importing country.

Flood *et al.* (1994) developed a method of fungicide application involving vacuum infiltration, which eliminated *Fusarium* spores from seeds, including any within the shell. This treatment should be applied whenever seeds are exported from areas where significant fungal diseases occur (see Section 7.1.5).

12.2 PESTS

The most important pests of oil palms are arthropods (insects, mites) and mammals, but other groups of animals may cause problems from time to time. In this section we have grouped the arthropod pests according to the damage that they do to the palm. We believe this arrangement will be more useful to the non-specialist than the conventional arrangement by zoological classification. We have attempted to give the correct Latin names for pest species, but taxonomic changes are regrettably frequent. For some species we have also given well-known but no longer valid names.

Wherever possible, growers should use integrated pest management (IPM) systems. These involve the encouragement of biological control of pests, the adoption of agronomic methods that minimise the risk of pest outbreaks and, if pesticide application is unavoidable, the use of selective chemicals and application methods with minimal side-effects. IPM has been widely applied in the oil palm industry for several decades, and much of the current understanding of the principles of IPM developed from work on tropical crops. As early as 1962, it was recognised that insecticides were causing pest attacks in oil palms, by upsetting the ecological balance between the pest and its natural enemies (Wood, 1971). In *Pests of oil palms in Malaysia and their control*, Wood (1968a) enunciated the principles of what was then known as integrated pest control, with more than one-third of the book being devoted to explaining the reasons for pest outbreaks, methods of monitoring pest populations and ways of controlling pests without disruption of the natural balance in the agroecosystem (see also Wood, 1976c, 1987). As a result of the understanding of pest

ecology that has been built up in all the main areas where the crop is grown, oil palms generally remain free of damaging pest outbreaks, without much need for intervention with insecticides.

Smith and Reynolds (1966) proposed an ecologically based classification of pests.

- Key pests are perennially occurring, and would cause severe damage in the absence of control measures. These are pests for which the limitation by natural enemies is generally inadequate.
- Occasional pests may cause sporadic economic damage, if the usually good environmental control, including biological control, is disrupted.
- Induced or potential pests cause no significant damage under current conditions, but have the potential to do so if environmental control were disrupted by changes in agricultural practice (usually the application of an insecticide).

This classification can be useful in considering how to manage a pest, although in practice it may be difficult to apply, as it refers to the natural balance between pests and their enemies, and not necessarily to that actually existing in the plantation.

There are no key pests of the oil palm, but a number of occasional pests can cause serious damage. For example, Wood *et al.* (1973) showed that a single bagworm outbreak, causing more or less complete defoliation of 10-year-old palms, reduced yield by 40–50% over the next 2 years. Many factors may disrupt natural balance, and when an outbreak does occur, it is important to try to understand what caused it. This can be difficult, because outbreaks may persist for some time after the original disturbance has disappeared. Wood (1979) suggested that this was because it can take time for natural enemy numbers to build up to match the numbers of pests. The more important occasional pests are discussed later in this chapter.

There are numerous potential pests. For example, in South-east Asia Wood (1968a) mentioned over 80 arthropod species; in Latin America, Mexzón and Chinchilla (1993) listed 41 species, and Genty *et al.* (1978) over 70; in Africa, Mariau *et al.* (1981) listed 22 species, and Wood (1983a) 26 species. Some potential pests are listed in Table 12.11.

We have not given detailed recommendations on pesticides, as these are constantly changing, with new compounds being developed and older ones withdrawn. The most recent general recommendations appear to be those of Mariau (1993) and Jacquemard (1998).

12.2.1 Integrated pest management

The important aspects of an IPM system can be summarised as follows.

- Knowledge of the life cycle and ecology of the pest, and of its natural enemies, is required, if biological control is to be understood and manipulated.
- A monitoring or census system to ensure early detection of outbreaks should be in place, so that control measures can be planned, and applied at the most appropriate time.
- Economic damage and action thresholds should be established, so that control measures are not taken unless and until they are necessary, giving the natural balance a chance to be re-established.
- Control measures must be selective, so that swift re-establishment of the natural balance is promoted.

Each of these aspects is discussed briefly below. For more detailed discussion in relation to oil palms, see Wood (1971, 1976c, 1979, 1987). Recent reviews are given by Teh (1996), Ho and Teh (1997) and Chung and Sharma (1999). Specific examples are also mentioned in the sections on individual pest species. Oil palm workers have not always adhered to IPM principles, though; numerous papers have been published describing potential oil palm pests and testing insecticides for control, without any evaluation of the severity of damage or the extent of natural control. Many of the older recommendations took no account of the possibilities of IPM. In some instances these have not been updated, probably because it has become apparent that control by natural enemies is sufficient, and no action is necessary.

12.2.1.1 Pest ecology

As Wood (1976c) pointed out, the environment in an oil palm plantation, with a uniform expanse of the crop and a more or less constant environment, would appear to favour the build-up of pests. Many occasional pests are commonly present in a stand of oil palms, and the reason that outbreaks do not usually occur is that numbers are restricted by the action of natural enemies; these include both predators on the pests and species that parasitise the pests. Outbreaks may occur if the natural balance between a pest and its enemies is upset for any reason.

One of the major factors in pest outbreaks in oil palms in the past was the use of broad-spectrum (killing a wide range of species), persistent-residue, contact insecticides. These were often applied as a precautionary measure against minor pest infestations, but their

Table 12.11 Potential oil palm pests

Pest	Stage attacked	Damage	Occurrence	Ref.	Comments
<i>Pests causing leaf damage</i>					
Red spider (<i>Olygonychus</i> sp.)	Nursery	Leaf turns brown, necrotic	Widespread	1	Often induced by pesticide application. Not a problem with overhead sprinkler irrigation
Aphids	Nursery	Growth rate reduced	Malaysia Congo	1, 2	Severity has not justified treatment
Mealy bugs, scale insects	Nursery, field	Leaf, fruit		2, 3	Often tended by ants; control of ants may eliminate pest; serious damage rare
Grasshoppers	Nursery	Defoliation	Widespread	2	Several species; hand-removal effective
Grasshopper, <i>Valanga nigicornis</i>	Young palms	Defoliation	Malaysia	2, 4	Particularly in new plantings, after drought; spraying may be necessary
Stink locust (<i>Zonoceros variegatus</i>)	Young palms	Defoliation	West Africa	2, 5	Damage followed slashing of overgrown covers
Leaf-cutting ants	Mature palms	Defoliation	Latin America	2	
<i>Alurnus humeralis</i>	Mature palms	Defoliation	Ecuador	6	Coleoptera: Chrysomelidae: Hispinae
<i>Homophylotis catori</i>	Mature palms	Defoliation	Africa	5, 7	Caterpillar: Zygaenidae (syn. <i>Chalconycles</i>)
<i>Leptonatada sjöstedti</i>	Mature palms	Defoliation	Africa	5	Lepidoptera: Notodontidae
<i>Hispoleptis</i> spp. (Hispinae)	Mature palms	Leaf miner	Ecuador	2, 8, 9	Damage similar to <i>Coelaenomenodera lameensis</i> ; control by trunk injection (Ref. 9)
<i>Promecotheca cumingi</i>	Mature palms	Leaf miner	Malaysia	1, 8	Coconut pest, occasionally attacks oil palm Coleoptera: Chrysomelidae: Hispinae
<i>Norape argyrrhorea</i>	Mature palms	Defoliation	Peru	18	Lepidoptera: Megalopygidae; controlled by virus
Beetles	Mature palms	Bore into petioles	Malaysia, Africa	2	<i>Xylotrupes gideon</i> , <i>Platygenia barbata</i>
<i>Retracus elaeis</i> , orange spotting mite	Field	Orange spots	Colombia	10	Eriophidae; may cause 50% crop loss; wettable sulfur gave effective control

Pests damaging trunk or roots

<i>Eldana saccharina</i>	Nursery	Larvae bore into spear/bud	Africa	5	Lepidoptera: Pyralidae
<i>Dynastes (Augosoma) centaurus</i>	Nursery, field	Similar to <i>Oryctes</i>	Africa	2, 5	Coleoptera: Dynastinae
<i>Scapanes australis</i>	Young field palms	Similar to <i>Oryctes</i>	SE Asia	11	Coleoptera: Dynastinae
<i>Sufetula</i> spp. (Lepidoptera: Pyralidae)	Mature palms	Destroy aerial roots	Widespread	5, 12	No evidence that loss of aerial roots is harmful
<i>Monolepta apicicornis</i>	Mature palms	Mines within root	West Africa	5, 13	Coleoptera: Chrysomelidae: Galerucinae
Termites (<i>Coptotermes curvignathus</i>)	Mature palms	Bore into trunk, palm falls	Malaysia, Indonesia	1, 11, 14	Should be eliminated at time of planting; may be a particular problem on peat (Ref. 15)
Cockchafer larvae	Nursery, field	Root damage	Malaysia	1, 16	<i>Leucopholis</i> , <i>Apogonia</i> , <i>Adoretus</i>
Cockchafers	Nursery, field	Leaf damage	Malaysia	1	

Pests damaging fruit

<i>Tiquadra</i> spp.	Mature palms	Spear, bunch	Colombia	2	Damage similar to <i>Tirathaba</i> (12.2.8.1)
<i>Prosoestus</i> spp.	Mature palms	Stigma damage, poor fruit set	West Africa	2, 17	Effect small, undamaged fruits enlarge to fill space of damaged; treatment expensive
<i>Elaeidophilos adustalis</i>	Mature palms	Stigma damage, poor fruit set	West Africa	17	Effect small; treatment expensive
Scale insects	Mature palms	Not serious		1	

References: 1: Wood (1968a); 2: Hartley (1988); 3: Ponnamma (1999); 4: Han and Chew (1978); 5: Mariau *et al.* (1981); 6: Mariau (1976b); 7: Airede *et al.* (1999); 8: Mariau (1999a); 9: Le Verdier and Genty (1988); 10: Genty and Reyes (1977); 11: Mariau *et al.* (1991); 12: Genty and Mariau (1975); 13: Mariau and Djob Bikoi (1990); 14: Mariau *et al.* (1992); 15: Lim and Silek (2001); 16: Wood and Ng (1969); 17: Philippe (1993); 18: Zeddam *et al.* (2003).

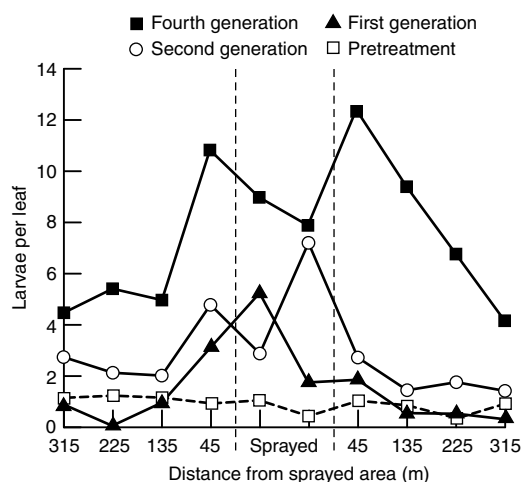


Fig. 12.3 Effects of dieldrin spray on population of *Metisa plana*. The population increased after spraying, centred on the sprayed area. (From Wood, 1971.)

use could exacerbate the problem, by killing the natural enemies of pests, so that any biological control ceased to operate. The pest which became a problem after spraying was not always the same as that which had provoked the initial precautionary application. The possible effect of spraying with a broad-spectrum chemical is clearly illustrated in Fig. 12.3. When a 0.8 ha plot of palms was sprayed regularly with a low dosage of dieldrin, the population of the bagworm, *Metisa plana*, built up considerably over the next four generations, spreading out from the sprayed area. Wood (1968a) noted that it is difficult to prove that insecticides have caused outbreaks, but the coincidence has been sufficiently frequent as to leave little doubt.

One reason why spraying with broad-spectrum chemicals can cause a pest outbreak is that it is likely that a few of the pests will survive the spraying, but almost none of their enemies, simply because the pest is usually present in larger numbers than its enemies. In that case, the pest can then build up uncontrolled. With contact insecticides, patchy or uneven application is likely to make matters worse, because the natural enemies are usually mobile and exploratory in their behaviour, so will move into sprayed patches, while the more static pest remains untouched elsewhere. Wood (1987) noted that a high kill of the pest with moderate survival of enemies was probably better than a moderate kill of the pest with complete survival of enemies. An additional factor is that only one particular stage in the life cycle of

the pest may survive; if so, then subsequent generations will be highly synchronised (e.g. Mariau, 1976a). Under normal conditions in the tropics, all stages tend to be present, and there has thus been no pressure for the natural enemies to evolve co-ordinated life cycles. If pest generations do become synchronised, natural enemies may be heavily outnumbered, so that control of the pest breaks down.

Pesticides are not the only cause of outbreaks, which sometimes occur in areas where pesticides have not been applied. Syed and Shah (1977) quoted circumstantial evidence to suggest that complete eradication of weeds by herbicide spraying had contributed to pest outbreaks in Sabah. They argued that weed species were important food plants for the adults of parasitic wasps; weed eradication thus reduced the level of parasitism and allowed pest numbers to build up. Prior (1988) demonstrated the importance of two weed species in supporting a wasp parasitic on grasshoppers in PNG (Section 12.2.5.4). Delvare and Genty (1992) recommended protecting and spreading certain weed species in Latin America, to support beneficial insects. In Malaysia, Ho (1998) showed that numbers of the bagworm, *Metisa plana*, were suppressed for about 200 m on each side of a planted strip of *Euphorbia heterophylla*, a species shown to be attractive to a wide variety of different insects.

Wood (1968a) suggested that dust from dry dirt roads in plantations might be a disturbing factor. Dust can kill insects by abrasion of the cuticle, and may affect the active natural enemy species more than relatively inactive pests such as caterpillars. Syed and Shah (1977) considered that any effect of this would only extend a few palms away from the road, but that pockets with high pest numbers might develop in consequence, which could then lead to larger outbreaks when other conditions were favourable. Siburat and Mojiun (1998) observed outbreaks of leaf-eating caterpillars after floods, which might have eliminated natural enemies whose adults lived on ground vegetation. They suggested that drought could have a similar effect.

Knowledge of pest life cycles can be useful, particularly when synchronised generations occur. Life cycles for many Malaysian pests were given by Wood (1968a). Siburat and Mojiun (1998) gave a life-cycle table for *Setora nitens*, showing the control measures appropriate for each stage. Studies of natural enemies can also be useful, although the enemies important under normal conditions may not be the most effective in containing outbreaks (Wood, 1979). Mariau *et al.* (1991) illustrated a number of the more important predators and parasites in South-east Asia.

12.2.1.2 Economic damage thresholds

Response should be related to pest numbers, rather than following a predetermined programme. Regular prophylactic pesticide applications can appear to give control, but by removing natural enemies, may ensure that the problem persists. Defining a critical level of a pest provides the necessary link between ecology and economics (Wood, 1979). A warning level may be useful, as an alert to potential danger. It is important also to understand whether the pest population is increasing, stable or decreasing.

As an example, studies of the damage caused by *Oryctes* in young oil palms have shown that, during the first year in the field, quite extensive defoliation has little or no effect on subsequent yield (Wood *et al.*, 1973; Liao and Ahmad Alwi, 1995). This appears to be because growth at that stage is not limited by photosynthetic activity, so after partial defoliation, the remaining leaves can photosynthesise more rapidly to meet requirements for vegetative growth (see Section 4.2.2.1 for further discussion of this). Some degree of control of *Oryctes* is needed, because the beetle may kill young palms, not just defoliate them. In addition, if damage persists into the second year, it starts to affect yield (Liao and Ahmad Alwi, 1995; Chung *et al.*, 1999). The important point, though, is that apparently severe damage in the first year may have little economic effect, and the control strategy should take account of this.

12.2.1.3 Census systems

If responses are to be based on pest numbers, then a regular monitoring system must be in place. Pest numbers may be counted directly, or an assessment of damage may be made. Monitoring systems for leaf-eating caterpillars were discussed by Wood (1976c). Most systems involve at least two stages: a superficial inspection for signs of pest incidence, the 'detection' stage, and more detailed assessment where such signs are found, the 'enumeration' stage. Chung *et al.* (1995) described a system for bagworms, based on unpublished work by Wood, with three stages.

1. The *alert* stage involves looking for the small holes in leaves, which are signs of feeding damage. This inspection can be undertaken by harvesters, and is frequent (fortnightly) but superficial.
2. When feeding damage is noticed, the *census* stage is activated. An upper frond from 1% of palms is cut down, and the number of individual bagworms and nettle caterpillars, both alive and dead, is counted by a specially trained team. The census is repeated

in affected areas every 1 or 2 weeks, different palms being used each time to avoid excessive defoliation.

3. The results of the census determine whether the *action* stage is needed. Control measures are implemented if the census in affected and adjacent blocks shows that all of the following conditions are met.
 - Infestation is spreading.
 - Natural control appears to have failed.
 - The pests are at the small larval stage, with cocoons absent or very few.
 - Numbers exceed 5–10/frond for the smaller species, or 1–5 for the larger, indicating that there is a high risk of crop loss.

Mariau (1994) gave a more general review of census systems in various parts of the world, together with a list of advice notes on pests published in *Oléagineux* between 1967 and 1994. The recommended frequency of the alert stage depends on the expected pest species. The choice of leaf for detailed recording will depend in part on the particular pest, as some damage young leaves and some older leaves (Wood, 1976c). The action level for a pest may depend on the weather; Mariau (1999b) noted that the leaf miner *Coelaenomenodera lameensis* multiplies more slowly during drought, so the action level can be higher.

12.2.1.4 Control measures

Various management practices are important components of IPM, in ensuring that outbreaks do not occur. The probable importance of the weed flora as food plants for natural enemies has already been mentioned. Ground cover also plays a role in limiting *Oryctes* damage (Section 12.2.4.1). Study of the life cycle of a pest may reveal an alternate host plant, the elimination of which from the plantation will help to control the pest.

If pesticide application is needed, it should be selective. Bio-insecticides (preparations of parasitic fungi or insect viruses, or *Bacillus thuringiensis*) can be effective (e.g. Desmiers de Chenon *et al.*, 1988; Sipayung *et al.*, 1990; Ramle *et al.*, 1995). The damaging effects of some of the older broad-spectrum, persistent-residue chemicals have already been mentioned, but some modern chemicals are also broad spectrum and can cause problems if wrongly used. The synthetic pyrethroids, for example, break down rapidly and have little residual effect in the tropics, but they are broad spectrum and repeated use can damage natural enemy populations.

Selectivity can be achieved not only by choice of chemical, but also by the timing and method of application. Knowledge of the pest life cycle may allow application to be timed to a stage when the maximum

kill can be achieved, while sparing natural enemies. For example, with *Coelaenomenodera lameensis*, spraying may be most effective against adults; larvae in galleries within the leaf lamina are protected from contact pesticides (Mariau, 1999b). One of the best methods of insecticide application to oil palms is by trunk injection (Wood *et al.*, 1974) or root absorption (Ginting and Desmier de Chenon, 1987). In this instance, the application method provides selectivity. A systemic pesticide moves into the leaves, and only species that eat the leaves will be affected. The risk of affecting non-target species is usually minimal, although Prior (1988) noted effects on crows and domestic chickens after they had eaten grasshoppers that had been treated by trunk injection of monocrotophos. Sarjit (1986) showed that trunk injection could be done effectively and economically on a large scale. The equipment is cheap and may have other uses. This is important, as where pest outbreaks are rare, equipment may remain unused for long periods.

Insect pheromones, volatile chemicals produced as signals to other insects, are increasingly being used in pest-control strategies. For example, female bagworms are wingless and immobile, and attract males by releasing a pheromone. Baiting traps with the pheromone to collect males could, clearly, disrupt mating and contribute to control of bagworms (Rhainds, 2000). Pheromone-baited traps may also be used for monitoring populations.

12.2.2 Nursery pests

Several potential nursery pests are listed in Table 12.11. Red spider mite may have severe effects, but is rarely a problem in nurseries irrigated by overhead sprinklers. Boron applications have been found to reduce spider mite injury (Rajaratnam and Law, 1975).

12.2.3 Leaf pests of immature palms

Most of the leaf pests of mature palms may also attack young palms. The pests listed in this section appear to attack mature palms only rarely, however.

12.2.3.1 The African spear borer

Distribution: This moth, *Pimelephila ghesquierei* (Pyralidae, Pyraustinae), first described from Congo, is found in all African territories. It is not a common pest, but on occasions the damage done has been severe. It has perhaps been more troublesome in Central than in West Africa.

Life cycle and damage: Damage is most common between the second and fifth years in the field, but both nursery seedlings and older palms are sometimes

affected (Buyckx, 1952). The eggs are laid by the moth at the base of the spear leaves and even one larva hatching can do considerable harm. Usually, two or three are found on young palms or up to a dozen on older ones and, typically, they penetrate the rachis and leaflets of the growing, unopened spears, forming galleries through them. The attack may proceed downwards towards the growing point and the rachis may be so damaged that later, in a strong wind, several young leaves may snap near the base. When unbroken spears open, the holes left by the caterpillar are seen to be symmetrically placed on either side of the rachis. The caterpillar does not kill the palm, but may be followed by weevil larvae, e.g. those of *Temnoschoita*, or a bacterial rot that may prove lethal (Buyckx, 1952).

The caterpillars reach a length of 3–4 cm before pupating in a cocoon of fibrous debris. The colour of the caterpillar changes from dark red to yellowish as it develops. The olive to brown moths are not long in emerging from the pupae and the whole life cycle takes 35–45 days; attacks can therefore be made at frequent intervals.

Control: Light attacks can be dealt with by removal of infected leaves and collection of the caterpillars and pupae. In the Ivory Coast spraying has been carried out at intervals of 2–3 weeks in nurseries and for the first 2 years in the field, but older palms are less vulnerable to attack and are not usually treated (Mariau and Morin, 1971).

12.2.4 Stem damage to young palms

12.2.4.1 *Oryctes species (Dynastinae): rhinoceros beetles*

Distribution: Species of *Oryctes* are found throughout the palm-growing areas of Africa, Asia and the Pacific. Damage is worst in young palms, and comparatively rare in palms older than 3 or 4 years, although Dhileepan (1988) recorded damage up to 15 years after planting in India, and isolated tall palms are often attacked.

The following species are the most important oil palm pests:

<i>O. rhinoceros</i>	The common rhinoceros beetle of the Far East, which has spread to the Pacific islands (Plate 12.5)
<i>O. gnu</i> (<i>O. trituberculatus</i>)	Asia, less common
<i>O. boas</i>	Probably the most common species in Africa
<i>O. monoceros</i>	Africa
<i>O. owariensis</i>	Africa

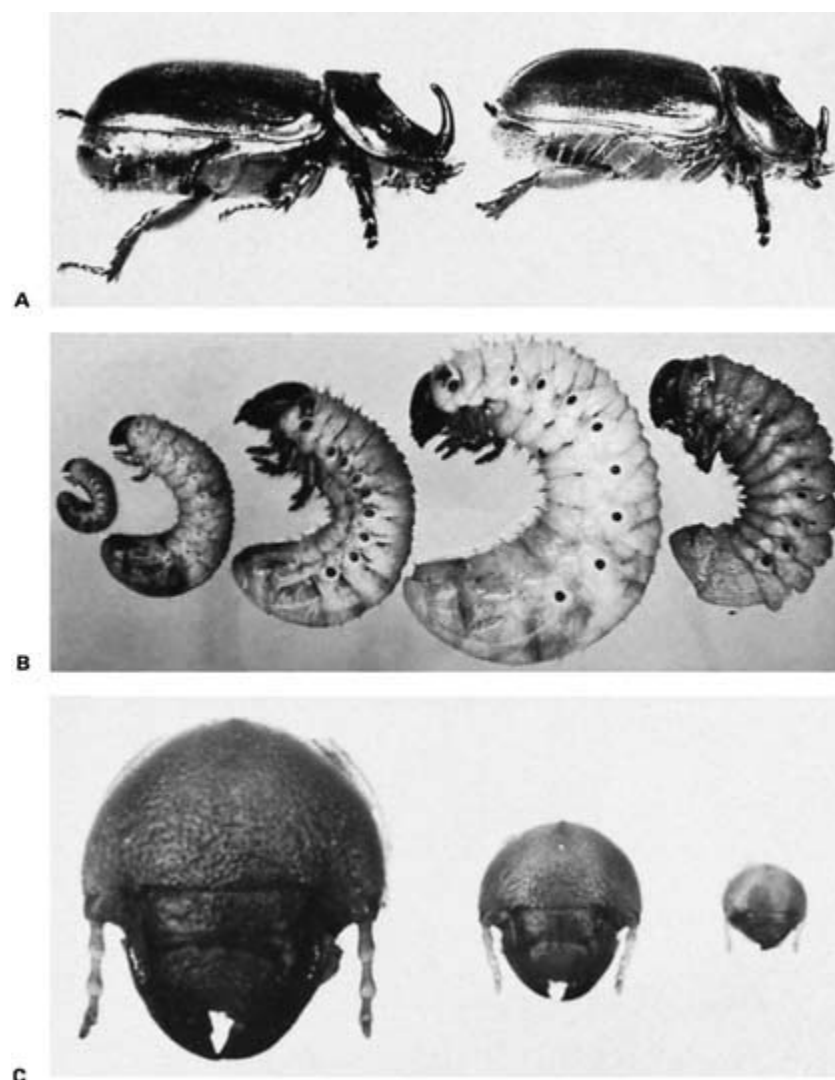


Plate 12.5 *Oryctes rhinoceros* in Malaysia. (A) Adults, male (right), female (left). (B) Larval instars, 1st, 2nd, 3rd (early, late, prepupal). (C) Head capsules of larval instars; (left to right) 3rd, 2nd, 1st.

The Asian species are primarily pests of the coconut palm, but they attack other palms, both cultivated and wild. The African species attack the coconut and *Borassus* palms but, owing to its ubiquity, the largest population is to be found on the oil palm.

Description, life cycle and damage: The male adult has the characteristic 'rhinoceros horn'; in the female the horn is smaller or, in the African species, is reduced to a triangular protuberance. The beetle is black and measures 4–6 cm long and 2–3 cm broad according to species, *O. trituberculatus* being larger than *O. rhinoceros*, and the African species *O. owariensis* being larger and

O. boas being smaller than *O. monoceros*. The horn of *O. boas* is particularly long and curved.

The eggs are white, 3–4 mm in diameter and easily observed on breeding sites. About 20 eggs are usually laid, but higher numbers have been recorded; they hatch after 11–13 days. The young larva is white at first, but its head soon becomes brown and its body blue-grey, then yellowish or greenish-white; it reaches a length of 4–10 cm. The duration of the larval stage varies considerably, ranging from around 100 to 200 days. Similarly, the adult stage may last for a few months or extend to over half a year. Before pupation there is a

short prepupal stage of a week; the adults emerge after a further 3 weeks. The eggs are laid on rotting vegetable matter. On an oil palm estate decaying palm trunks and bunch refuse are common breeding grounds. Empty bunches stacked prior to use as mulch may be a problem; the length of the larval stage is such that spreading should usually be done before pupation takes place, but the life cycle may sometimes be completed.

The oil palm is damaged by the adult beetle, which burrows into the cluster of developing spears in the crown and bores its way through the petioles into the softer tissues of the younger, unopened leaves. The effect can be seen when these leaves develop and open, but the regularity of wedge-shaped cuts so characteristic with the coconut palm is not always so clearly seen in the oil palm. Where the rachis has been penetrated, leaves may later snap off. Previous attacks may be detected by the presence of holes in the petioles of older leaves. Attack is most damaging in young palms, since the growing point is occasionally reached, or bud rot may develop and kill the palm. The holes may also give *Rhynchophorus* access to the palm (Section 12.2.6.1), with *Rhynchophorus* damage, in turn, providing conditions suitable for *Oryctes* larvae (Zulnerlin and Fatah Ibrahim, 1999).

Apart from the occasional young palm that is actually killed, the effect of *Oryctes* damage on yield may be very small. Wood *et al.* (1973) compared two 2.4 ha plots, one with over 80% severe or medium damage by *Oryctes*, and one with only 6%, and found that the former yielded 2% less over the first 18 months of production. In this trial, damage probably ceased at least a year before harvesting started. Later damage can have more effect. Liau and Ahmad Alwi (1995) found that artificial defoliation of 2-year-old palms did affect yield: 50% defoliation on a single occasion reduced subsequent yield by 12%, and repeated ('chronic') defoliation reduced it by 24%. Chung *et al.* (1999) found that palms damaged by *Oryctes* 21 months after planting yielded 80% less than undamaged palms in the first 12 months of production (although this comparison was based on groups of only 20 palms). With more than 70% of palms damaged, they estimated a loss of 2.1 t FFB/ha in the first year. Liau and Ahmad Alwi (1993) observed less damage in the second year in the field, and harvested 5 t more fruit over the first 18 months of production from palms in a clean clearing than from plots with windrowed trunks.

Control: Older methods of control involved destruction of breeding sites, and hand-collection of adult beetles. Hartley (1988) advocated that all rotting vegetable matter should be dispersed and rotting palm trunks

disposed of. Where the palm trunks were not burnt, regular inspection to break up the rotting material and collect larvae was recommended (Barlow and Chew, 1971). This method was labour intensive, but Zulnerlin and Fatah Ibrahim (1999) found that in Indonesia hand-picking was cheaper than insecticide application. In some countries, the larvae are hand-picked and cooked and eaten as a delicacy. Complete pulverising of trunks to sawdust-sized particles, thus largely eliminating breeding sites, has been claimed to reduce the population to less than 3% of that with the usual chipping, which cuts the trunk into fragments weighing 1.5–8 kg (Ooi *et al.*, 2001).

It was noticed in Malaysia that palms along or near roadsides might be heavily attacked while those within the field escaped injury, and Wood (1968b) showed that interrow vegetation may form a barrier to beetle movement and, in young areas, may blur the palm silhouette which is believed to attract the beetle. When areas of young palms either kept bare or sown with a legume cover crop were compared, *Oryctes* breeding and damage were considerably higher on the bare areas (Wood, 1968b). In addition to its many other advantages, the planting of leguminous cover is undoubtedly an effective way of suppressing *Oryctes* attack. It has been confirmed that this approach is also effective against *O. monoceros* in Africa (Boyé and Aubry, 1973). Wood (1976a) noted that ground cover does not totally eliminate attack, but reduces it to a very low frequency, such that effects on yield are unlikely to be important. He suggested that *Oryctes* attack is rare on older palms, because the closed canopy itself forms a 'vegetative barrier'; as noted above, isolated older palms are often attacked.

Ethyl chrysanthemumate was found to be a strong attractant to *Oryctes*, and Turner (1973) suggested baiting traps with this compound, but Wood (1976a) thought that the density of traps required (25/ha) was too great for the method to be cost-effective. Hallett *et al.* (1995) found that the aggregation pheromone, ethyl-4-methyloctanoate, was ten times more attractive to *Oryctes* than ethyl chrysanthemumate. This allows a much lower trap density, and Chung (1997) showed that one trap per 2 ha gave good control of damage, provided that the *Oryctes* population was not too large. Costs were lower than for insecticide application. Where risk of attack is thought to be high, a systemic insecticide (carbofuran) may be applied. Desmier de Chenon *et al.* (1998) advocated trapping in the old stand for 6 months before replanting, to reduce the population. N. Kamarudin *et al.* (1999) suggested using pheromone trapping to monitor beetle populations and

identify 'hot spots' where chemical control would be worthwhile.

Much attention has been paid to the introduction and spread of insect parasites, fungi or viruses. A virus, *Rhabdionvirus oryctes*, first identified in Malaysia (Huger, 1966), has been introduced over most of the South Pacific where *O. rhinoceros* is a coconut pest. Infected beetles stop feeding, and fly and mate less frequently (Zelazny, 1977), and beetle populations have been reduced following introduction of the virus (Young, 1986). In Malaysia, there is a regular, although small, larval mortality from the virus (Barlow and Chew, 1971), and it is likely that the virus and its host have reached an equilibrium. Barlow and Chew (1971) also identified a fungus, *Metarhizium anisopliae*, which infects the larvae; Tey and Ho (1995) applied cultures of this to *Oryctes* breeding sites and achieved high infection rates, coincident with reduced numbers of larvae. Ho (1996) recommended an integrated approach to *Oryctes* control, involving pheromone traps, release of trapped beetles inoculated with *Metarhizium*, inoculation of breeding sites with the fungus, and the use of synthetic pyrethroids when damage reached unacceptable levels. He quoted costs equivalent to about 3 t FFB/ha in the first year of production. Given the rather small effects of *Oryctes* damage on yield, noted above, it must be doubtful whether such measures are justified. It should also be noted that Hochberg and Waage (1991) used a model to show that, if *Metarhizium* were to be applied to a population already regulated to low levels by a virus, the ensuing mortality may result in the virus being eliminated from the population, so that a later resurgence of *Oryctes* may occur.

There is a view that the adoption of zero-burn replanting methods has increased problems with *Oryctes*, but we should not forget that, until about 30 years ago, all replants were zero-burn. The belief that the old stand must be completely uprooted to prevent *Ganoderma* attack (which may have little foundation; see Section 12.1.6.3) led to burning or windrowing of the old trunks. Where windrowing was done, if the old trunks were not adequately covered by vegetation, *Oryctes* could invade. Wood (1999) noted that there have been *Oryctes* outbreaks in recent years, which have led some to question the 'vegetative barrier' effect mentioned above, but he considered that in such cases there was always some evidence that development of vegetation cover had been restricted, for example by felling too late after poisoning, by stacking the palm trunks well above the vegetation, or by flooding.

Kamarudin and Basri Wahid (1997) surveyed 640 estates in Malaysia, with a total of 280,000 ha of immature palms. *Oryctes* infestations were reported from

16% of the area, with 13% of outbreaks described, subjectively, as 'serious' or 'very serious'. However, only 3% of outbreaks were in palms older than 18 months, and we have seen that before that age damage has little effect on subsequent yield.

Samsudin *et al.* (1993) found much higher *Oryctes* numbers in an underplanting than in an area where the old stand had been felled and trunks chipped before planting. Incidence was particularly high if the underplanted old stand was poisoned and left standing, as expected from the absence of vegetation cover. Similar observations have been used as an argument against underplanting (Section 8.3.4.3), but provided that the old stand is felled and quickly covered by ground vegetation, there should not be a problem (Hakim *et al.*, 1998). If *Oryctes* does build up in an underplanting, though, there could be significant effects on yield. If the last of the old stand is cleared 2 years after underplanting, there might be damage to palms aged 2 years or more, and damage at that age has been shown to affect yields (see above). Jacquemard *et al.* (2002a) found large differences between oil palm families in amount of damage (though with no indication of statistical significance), and considered that some genotypes were more attractive to *Oryctes* than others. While this might not be important for seed production, they suggested that it should be considered in clone selection.

Conclusion: If a good legume cover is established early in an oil palm replant, this effectively suppresses *Oryctes*, and the amount of damage to young palms should be small. As it has been clearly established that quite severe defoliation during the first year in the field has little effect on subsequent yield, in most situations it is unlikely that *Oryctes* control measures will be needed. Only if severe damage continues beyond the first 18 months in the field would the possible loss in yield justify treatment.

12.2.4.2 *Strategus aloeus* (Dynastinae)

This beetle, which somewhat resembles *Oryctes*, is distributed throughout tropical America, where it has been troublesome in several oil palm plantations (Mariau, 1976b).

Incidence and damage: The adults attack young palms in the field or nursery by digging a hole in the ground near the palm, from which they bore their way into the plant just above the roots. Often, in a young palm, the growing point is reached and the plant killed. Eggs may be laid in the palm, which is then consumed by the developing larvae, or in rotting stumps, trunks and vegetation.

Control: In view of the lethal attack on young palms by the adult, control measures are required in areas where the beetle is common. As eggs may be laid in rotting stumps and trunks, the measures to be taken against the larval stage are the same as for *Oryctes* species: destruction of breeding sites and collection of larvae. During wet weather fortnightly inspections have been recommended; in dry weather *Strategus* attack is rare.

It does not appear to be recorded whether the 'vegetative barrier' effect which controls *Oryctes* is effective against *Strategus*.

12.2.4.3 *Temnoschoita* species (*Curculionidae*)

These weevils are found throughout Africa, but appear to be more common in Congo than in West Africa. The most common species is *T. quadripustulata* (*T. quadrimaculata*); *T. delumbata* is less common. Young palms may be killed, but the pest appears to cause no significant damage to mature palms (Mariau *et al.*, 1981) (Plate 12.6).

Life cycle and damage: Asante and Kumar (1986) described the life cycle of *T. quadripustulata* in Ghana. The adults are 8–10 mm long and dark brown, with the thorax spotted with indentations. The light brown wing cases have four reddish blotches and do not fully cover the abdomen. The females lay their eggs on cuts and wounds on the leaf petioles. On young palms, both those recently transplanted and palms in early bearing, and on nursery plants the young larvae tunnel their way through both dead and living tissue towards the heart of the palm, and pupate in the tunnels formed. The damage is sometimes severe, and young palms may be



Plate 12.6 *Temnoschoita* damage to leaves in West Cameroon. Note typical 'windows'.

killed through penetration to the growing point. In bearing palms the adults are attracted to the inflorescences, where eggs are also laid.

Control: In areas where the weevil has been noted, care should be taken to avoid wounding the palms by excessive leaf pruning, particularly just before transplanting (Buyckx, 1952). This injunction may conflict with control measures against *Cercospora* leaf spot (Section 12.1.2.1), and it may be useful to treat pruning cuts with tar. With bearing palms the collection and destruction of rotted bunches and scattered fruit are also recommended, as these may contain eggs, larvae and pupae. When harvesting begins it may be advantageous to undertake a general cleaning of the crown followed by dusting with an insecticide at intervals of 3 weeks, the dust being applied in the crown from the centre to the base, not on the leaves. Traps for the adults have been constructed from recently cut and split petioles or banana trunks (Buyckx, 1952). Banana plants are an attractive host and should not be grown near nurseries or young plantations where infection with *Temnoschoita* is feared.

12.2.5 Leaf pests of mature palms

Numerous species eat leaf tissue of mature palms and have the potential to cause significant defoliation. The effects of this on yield were investigated by Wood *et al.* (1973), who used manual defoliation to simulate the effect of attack by a leaf-eating pest on 8-year-old palms. Figure 12.4 shows that, in the first year after defoliation, 50%

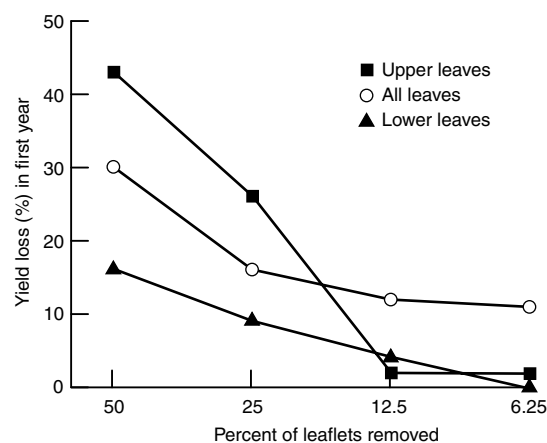


Fig. 12.4 Effects of artificial defoliation on subsequent yield. Different degrees of defoliation were applied by stripping off leaflets, to upper leaves, lower leaves or all leaves. (From Wood *et al.*, 1973.)

damage caused a crop loss of over 40%, if restricted to the upper half of the canopy (i.e. all leaflets in the upper half destroyed). This corresponded well with observations in a severely attacked area. Damage to the lower leaves had comparatively little effect, because those leaves are shaded by younger leaves at the top of the canopy, and contribute relatively little to total canopy photosynthesis. Less severe damage caused smaller losses.

The most severe treatment caused a further 17% crop loss in the second year. Study of monthly yields showed that there was a large shortfall about 10 months after defoliation, attributable to inflorescence abortion, and a further shortfall between 22 and 26 months, due to an effect on sex ratio (see Chapter 4 for discussion of these yield components). A mature oil palm canopy consists of about 40 leaves, and as leaf production rate is around 24 per year, the palm will take over a year to recover from damage to the younger, upper leaves.

This study allows economic damage levels to be estimated for any pest that causes defoliation. Wood (1977) noted that the cost of treatment by aerial spraying or trunk injection would be covered by a yield gain of no more than 3%. Figure 12.4 suggests that even quite mild defoliation could cause a loss of that order. The question, then, is not whether the cost of spraying will be recovered, but whether the outbreak will come under natural control anyway. If surveys indicate that numbers are increasing, and if a proven integrated control measure, such as trunk injection or an insect pathogen, is available, it will be advisable to take action at a fairly early stage.

12.2.5.1 Leaf-eating caterpillars

A wide variety of different caterpillars feeds on oil palm leaves. Nettle and slug caterpillars and bagworms are the most frequent pests. Mariau *et al.* (1991) presented good colour photographs of most of the important species, and of their natural enemies, but little information on control. Syed and Saleh (1993) described IPM systems for these pests in Indonesia.

Nettle and slug caterpillars: Members of this group, the Limacodidae, have been recorded as pests in all oil palm-growing areas. Wood (1987) listed the species that have been recorded as causing significant damage to oil palms (Table 12.12) and other crops. Some species, such as *Darna trima*, are common, yet severe damage may be unusual. Outbreaks of several species have been attributed to prior use of contact insecticides.

Life cycles and damage: Severe infestations may develop rapidly, as the life cycles are only a few weeks long and reproduction rates are high. The eggs are

deposited on the leaflets; the caterpillars usually feed on the underside, often stripping the surface when young, but when larger they may eat away the whole lamina, leaving only the midrib (Plate XVIIA). Pupation may be on the ground, in cracks in the soil, or attached to the leaf.

Mariau *et al.* (1991) gave critical levels, in terms of number of larvae per frond, for most species in South-east Asia, together with recommendations on insecticides. Different species attack different parts of the crown: *D. trima* is first found on leaves 9–17, *Setothosea asigna* and *Setora nitens* (Plate XVIIB) on leaves 9–25, and *Ploneta diducta* and *P. bradleyi* on older leaves (Mariau *et al.*, 1991). In severe outbreaks the entire crown may eventually be defoliated. The effect on yield depends on the extent of defoliation, and on which part of the crown is damaged. As noted above, loss of young leaves is more damaging than loss of older leaves.

Control: Numerous parasites and predators of the Limacodidae have been recorded. Species attacking *S. nitens* (Plate XVIIID) included five species of wasp, four parasitic flies and a bug (Wood, 1966, 1968a). *Setothosea* and related species are attacked by a virus, a fungus (*Cordyceps* sp.), and several predatory or parasitic insect species (Tiong, 1979).

Wood *et al.* (1977) described a series of experiments on the control of nettle caterpillars in Malaysia. They tested a range of chemicals and *Bacillus thuringiensis* insecticides, and considered the latter to be very promising. The trials confirmed the need for chemical intervention on occasion, choosing insecticides on grounds of good kill, selectivity, low cost and low toxicity to humans. The utilisation of diseased pests by spraying suspensions of crushed bodies was in several cases very successful. Tiong (1982) described control of *Setothosea asigna* by an integrated programme similar to that advocated by Wood *et al.* (1977), in which chemical intervention was confined to quelling high-density infestation and combined with the encouragement of the natural fungal and insect enemies. In Sarawak, good progress has been made with the control of *Darna trima*. A virus inoculum was prepared from diseased late-instar larvae, and from healthy larvae confined with them. The larvae were naturally infected by the virus and the inoculum was prepared by simple maceration, straining and dilution with water. This was sprayed with mist blowers, repeated until the larval census showed that resurgence was not taking place. There was a high mortality within 8 days in comparison with unsprayed areas, and resurgence, such as was common after 5 weeks with chemical insecticide spraying, did not take place (Tiong and Munroe, 1977).

Table 12.12 Nettle and slug caterpillars reported to have reached outbreak levels on oil palms

Species	Synonym	Location	Frequency ^a	Ref.
<i>Susica malayana</i>	<i>S. pallida</i>	W Malaysia	Occasional	1
<i>Setothosea asigna</i>	<i>Thosea asigna</i>	W Malaysia, Sabah	Often	2
<i>Setora nitens</i>		W Malaysia, Sabah, Sumatra	Frequent	2, 3
<i>Birthosea bisura</i>	<i>Thosea bisura</i>	W Malaysia	Occasional	2
<i>Ploneta diducta</i>	<i>Darna diducta</i>	W Malaysia	Occasional	2, 3
<i>Darna trima</i>		W Malaysia	Often	2, 3
		Sabah	Often	4
<i>Darna mindanensis</i>	<i>Darna</i> sp. nr. <i>trima</i>	Philippines	Often	2
<i>Darna furva</i>		South Thailand	Often	5
<i>Darna catenatus</i>		Sulawesi	Often	6
<i>Thosea vetusta</i>		Borneo	Occasional	3
<i>Parasa pallida</i>	<i>Latoia pallida</i>	West Africa	Often	7
<i>Parasa viridissima</i>	<i>Latoia viridissima</i>	West Africa	Often	7
<i>Episibine intensa</i>		Guyana, Colombia	Frequent	8
<i>Episibine sibirides</i>		Peru	Often	8
<i>Euclea diversa</i>		Central & S America	Often	8
<i>Euclea cuprostriga</i>		South America	Often	8
<i>Euprostema elaeasa</i>	<i>Darna metaleuca</i>	Central & S America	Frequent	8, 9
<i>Natada pucara</i>		Central & S America	Occasional	8
<i>Natada subpectinata</i>		South America	Occasional	8
<i>Sibine fusca</i>		South America	Occasional	8
<i>Sibine nesea</i>		South America	Occasional	8

^a Occasional: one or two recorded outbreaks only; frequent: extensive, heavy and recurrent outbreaks in more than one location, for some period of time; often: intermediate between occasional and frequent.

Based on Wood (1987).

References: 1: Wood (1968a); 2: Wood *et al.* (1977); 3: Ho and Sidhu (1986); 4: Wood and Nesbit (1969); 5: Wood (1987); 6: Mariau *et al.* (1991); 7: Mariau *et al.* (1981); 8: Genty *et al.* (1978); 9: Genty (1976).

The biology of *Euprostema elaeasa*, which is among the more serious of the numerous South American caterpillar pests, was studied by Genty (1976), who found several important parasites, including a wasp, *Casinaria* sp. Genty recommended that the parasite population be carefully examined before control measures are decided upon. *Sibine fusca*, another American species, is attacked by several bugs, and Genty (1981) recorded a wasp, *Apanteles* sp., and two flies, *Palpexorista coccyx* and *Systropus nitidus*, which not only parasitise the larvae but also transmit a viral disease (Meynadier *et al.*, 1977). This virus can be artificially spread: 20 g of infected larvae macerated in 220 ml of water and applied at 50 ml/ha was shown to spread the disease over the whole population within 18 days. Mexzón *et al.* (1996) controlled *S. megasomoides* in Costa Rica by spraying with *B. thuringiensis* and deltamethrin.

Species of *Parasa* have defoliated oil palms in West Africa. Specimens from Cameroon, Nigeria, Liberia and Uganda have been identified as *P. viridissima*, while *P. pallida* has been a pest of oil palms in the Ivory Coast (Mariau and Julia, 1973; Mariau *et al.*, 1981). Normally,

fungi and natural predators and parasites keep the populations in check by attacking the larvae and pupae. In the Ivory Coast, spraying 3 weeks after the appearance of the first caterpillars has been recommended (Mariau and Julia, 1973). Fediere *et al.* (1990) described the use of a virus for control of *P. viridissima*.

Monitoring: A pheromone produced by the female of *D. trima* has been identified by Sasaerila *et al.* (2000), who suggested that it could be used to trap males and hence to monitor the population. Desmier de Chenon *et al.* (1996) recommended using pheromone traps for monitoring populations of *S. asigna*. They indicated that this was cheaper than conventional census systems, and might give an earlier warning of pest build-up.

12.2.5.2 Bagworms

Several members of the Psychidae have been pests of the oil palm in Asia since the start of the plantation industry, but the prevalent species appear to have changed. In the period between World Wars I and II *Mahasena corbetti* was extensively studied, but since

1945 *Pteroma pendula* (formerly *Cremastopsyche pendula*) and *Metisa plana* have been the common species in Malaysia. In Indonesia *M. corbetti* is the principal species, and it can be a serious pest throughout South-east Asia. As with nettle caterpillars, effects on yield will depend on the extent of defoliation.

Life cycle and damage: The larvae of bagworms are encased in bags constructed of pieces of leaf bound with silk. *Metisa plana* and *P. pendula* feed on the upper surface of the leaf, the scraped portion first becoming dried out and then forming a hole. Further damage is done by the removal of pieces of leaf to make the case. Badly damaged leaves soon dry up and this gives the lower and middle part of the crown a characteristic grey appearance, the only green leaves being the youngest. *Mahasena corbetti* feeds on the undersurface of the leaf. Surviving caterpillars pupate in their cases on the underside of the leaves.

The size and form of the bags and the manner in which they are attached to the leaf help to distinguish the species. *Metisa plana* has a short, hooked attachment and the bag is about 13 mm long (Plate 12.7). The case of *P. pendula* is about 6 mm long, is rather rough and hangs on the end of a long vertical thread. *Mahasena corbetti* is much larger and the case is more ragged (Plate XVII); Syed *et al.* (1973) studied the life cycle of this species. The male moths of all species fly from their cases, but the females are wingless and remain in the case. They attract the males with a pheromone and mate while still in the case, each then laying 100–300 eggs. On hatching, the caterpillars acquire their own cases and feed in groups. The life cycles take between 2.5 and 4.5 months (Syed, 1978).

Kamarudin *et al.* (1996) described 18 species of parasitoid associated with *M. plana* and *M. corbetti* in Malaysia. The caterpillars die in large numbers from parasitic and predatory attacks and other causes, but explosions of population may occur locally from time to time when the natural balance is disturbed for one reason or another. The probable role of contact insecticides, sprayed both against other minor pests and against the bagworms, in these population explosions has already been mentioned.

Control: Owing to the risks associated with broad-spectrum contact insecticides, hand-picking was long recommended for small attacks, and stomach poisons such as lead arsenate or trichlorfon (which has short-lived residues) for larger outbreaks. Aerial spraying over wide areas was successful with trichlorfon (Wood, 1968a). Later, the systemic insecticide monocrotophos, applied by trunk injection, was found to be effective (Wood *et al.*, 1974). The injection was done by pouring



Plate 12.7 Bagworms in Malaysia: (left) *Metisa plana*; (right) *Pteroma pendula*. (B.J. Wood.)

the chemical into holes made with modified chainsaw drills. Tractor-mounted generators with electric drills and special equipment for immediate injection following drilling may now be used (Sarjit, 1986); one team with a tractor and two drills can treat 15–20 ha in a day.

Syed and Saleh (1993) described a census system for *M. corbetti*. Syed and Saleh (1998) achieved effective control of this pest by spraying part of an infested area with a granulosis virus. Basri Wahid *et al.* (1996) tested preparations of *B. thuringiensis* against *M. plana* and *M. corbetti*. The best preparation was as effective as trichlorfon, but some were much less effective. Rhainds (2000) suggested that control should be possible using pheromones to trap males and disrupt mating; this has been done successfully with another bagworm species, *Thyridopteryx ephemeraeformis* (Klun *et al.*, 1986).

Chung and Sim (1993) discussed a situation where bagworms had become a constant problem in a particular area, and were apparently not easily controlled. They showed that standard procedures (census twice per month, trunk injection where the threshold of ten larvae per leaf was exceeded), provided they were correctly followed, could reduce an apparently chronic infestation within a few months to a level where natural enemies took over control.

Ho (1998) demonstrated the value of *Euphorbia heterophylla*, a ground cover species which supports several of the natural enemies of bagworms, in minimising build-up of *M. plana*.

Other bagworms: Wood (1968a) mentioned species of *Pteroma*, *Clania* and *Amatissa* as showing limited

increases in Malaysia from time to time. *Oiketicus kirbyi* occurs in Costa Rica (Genty *et al.*, 1978).

In Colombia and Ecuador, *Stenoma cecropia* (Stenomidae) has occasionally caused extensive damage. This species has a fixed bag, and eats by journeys from it while remaining attached by fibres (Genty, 1978). There are some natural enemies, but control by them is reported to be weak and, in serious outbreaks, aerial spraying with trichlorfon has been necessary for effective control.

12.2.5.3 Other caterpillars

Damage by caterpillars of other families is also reported from time to time. *Homophylotis catori* (formerly *Chalconycles*) (Zygaenidae), which has a life cycle of about 30 days, was reported as causing serious local damage in the Ivory Coast (Genty, 1968). Outbreaks followed the use of BHC against leaf miner. *Pyrrhochaleia iphis* (Hesperiidae) and *Epimorius adustalis* (Psychidae) have been reported from Congo (Frazelle and Buyckx, 1962).

In Malaysia, Wood (1968a) and Mariau *et al.* (1991) recorded a large number of leaf-eating caterpillars, few of which, however, have done any significant damage. Cutworms (Noctuidae), usually *Agrotis* sp., can cause damage in prenurseries and *Spodoptera litura* may strip the leaf epidermis in nurseries.

In America, colonies of mixed species of Lepidoptera have characteristically developed on some plantations, and the method and timing of control has influenced the balance between species. *Opsiphanes cassina* (Brassolidae) did much damage as a leaf eater and was reported to be encouraged by carbaryl spraying, but reduced by using lead arsenate or *B. thuringiensis* (Rojas-Cruz, 1977). In the mixed colonies there have been species of *Megalopyge* (Megalopygidae), species of Dalceridae and Hesperiidae, and *Herminodes insula* (Noctuidae) in the spear leaf, and some Psychidae.

12.2.5.4 Grasshoppers

Bush crickets, long-horned grasshoppers or treehoppers (Tettigonidae) are described as the principal pest of oil palms in PNG (Prior, 1988; Caudwell, 2000). Three species, collectively known as Sexava, are oil palm pests: *Segestes decoratus*, *Segestidea defoliaria* and *S. novaeguineae*. Prior (1988) noted 80–90% defoliation by *S. defoliaria*. Prior listed a number of species parasitic on Sexava, but according to Caudwell (2000), experience suggests that populations are not well controlled by natural enemies; once light damage is observed, this will steadily increase until severe defoliation has occurred.

Control: Bush crickets can be controlled by trunk injection of monocrotophos (Prior, 1988), but treatment must be in the early stages of an outbreak to be effective. Caudwell (2000) described a census system based on the amount of visible leaf damage, rather than on pest numbers. Mass rearing and release of egg parasites was described by Prior (1988), but it seems that these methods do not give complete control, and further work on biological control methods is in progress (Kathirithamby *et al.*, 1998; Caudwell, 2000).

12.2.5.5 Leaf miner, *Coelaenomenodera lameensis* (*C. minuta*, *C. elaeidis*)

This beetle is found on oil palms and, to a lesser extent, on coconut and *Borassus* palms throughout West and Central Africa. Serious attacks, causing widespread defoliation, have been reported from Ghana, Benin, the western part of Nigeria, Ivory Coast and West Cameroon, although for a long period the leaf miner was only reported from Ghana. There are numerous species of *Coelaenomenodera*. Until 1980, the main oil palm pest was thought to be *C. elaeidis*, but then two species were recognised, with *C. minuta* thought to be the more important. It now appears that the pest is a third species, *C. lameensis* (Berti and Mariau, 1999). Although *C. elaeidis* occurs on oil palms, it is not thought to be involved in outbreaks (R. Philippe, pers. comm., 2001).

Life cycle and damage: The method of feeding and life history were recorded in Ghana by Cotterell (1925). Very detailed studies have been made of the biology of this insect and of its control (reviewed by Mariau, 1976a). The life history in days is as follows: eggs, 20; larvae, 44; pupae, 12; adult to egg laying, 18; total, 94. The adults continue to live on the undersurface of the leaf for 3–4 months during and after laying eggs. The length of the life cycle accounts for the pest damage reappearing in some cases every 3 or 4 months.

A single female of *C. lameensis* may lay several hundred eggs; *C. elaeidis* is less prolific, perhaps explaining why outbreaks of that species do not occur (R. Philippe, pers. comm., 2001). The larvae, which grow to about 7 mm in length, are brown and their heads are squeezed into the thorax, their flattened bodies being transversely divided by deep furrows. They mine under the upper epidermis of the leaflets of palms of all ages except, normally, those below 3 years old in the field. The galleries are longitudinal, and in a severe attack the greater part of the leaf tissue will be destroyed (Plate XVIC). A single gallery mined by a larva to attain its full development measures about 15 cm in length and is 1 cm broad. Severely attacked palms have a typical appearance; the

young leaves are green, being little attacked, while the remainder are grey-brown and withered, with desiccated, rolled-in leaflets. Later, the withered laminae shatter, leaving the leaflet midribs only.

The pupae are found in the dead tissue of the leaves, and the adults, which are 4–5 mm long, emerge after about 12 days. The pupae are mobile and are found in the centre of the galleries. The adult emerges through the upper epidermis and shows a preference for migrating to the higher leaves. These adults are pale yellow with reddish wing cases; they also do some damage, making grooves about 1 cm long on the leaflets. The female lays her eggs in a small cavity on the underside of the leaf.

The effect of damage on yield is similar to that of other pests which cause defoliation. Philippe *et al.* (1979) estimated that there was a 40% yield loss in the 2 years following an outbreak.

Control: The census method developed in the Ivory Coast (Mariau and Bescombes, 1972) involved counting of adults and larvae on a leaf between 25 and 30 (i.e. in the lower part of the canopy), with small and large larvae, nymphs and adults being recorded separately. The palms selected for counting are changed at each census round. Counting is done every 3 months when the number of larvae is below 10 and of adults below 1; monthly when the numbers are 10–20 and 1–3, and weekly if more than 20 and 3, respectively. When the latter stage is reached treatment is considered necessary.

Spraying with Evisect (thiocyclam), using a tractor-drawn sprayer or a helicopter, or by fogging, was recommended by Philippe (1990a, b). A single treatment was usually effective, but sometimes a second application 3 weeks after the first was needed. There was only a small effect on the population of the pollinating weevil, *Elaeidobius kamerunicus*, and there were no detectable residues of thiocyclam in palm oil. Trunk injection has also been recommended (Philippe and Diarrassouba, 1979); with suitable equipment, this is easily done over large areas (Sarjit, 1986).

Cotterell (1925) reported hymenopteran parasites of both the eggs and the larvae, as well as fungal parasitism. In the drier parts of the West African palm belt where leaf miner damage has been serious in some years, the attacks seem ordinarily to have been controlled by natural predators, and resurgence has not occurred again until, for some reason, the parasite population has fallen below normal. Parasitism of *Coelaenomenodera* was studied in detail by Morin and Mariau (1974), Mariau and Morin (1974) and Mariau *et al.* (1978). The eggs are parasitised by the chalcid fly, *Achrysocharis leptocerus*, and by *Oligosita longiclavata* (Trichogrammatidae). There were three larval parasites: the eulophid flies *Sympiesis*

aburiana, *Pediobius setigerus* and *Cotterellia podagrica*. None of these was sufficiently numerous to have much limiting effect in outbreaks (Mariau *et al.*, 1978), so a search has been made for possible parasites to introduce into the Ivory Coast for control of the pest. The eulophid wasp, *Chrysonotomyia* sp., was successfully introduced from Madagascar, but it failed to parasitise *C. lameensis* (Lecoustre *et al.*, 1980). In Cameroon, Timti (1991) found that leaf miner attacks were fewer where *Crematogaster* ants were present, and suggested that the pest could be controlled by collecting these ants and distributing them in affected areas.

12.2.6 Stem pests of mature palms

12.2.6.1 *Rhynchophorus* species (Curculionidae): palm weevils

Rhynchophorus is a potentially lethal pest. In Asia and Africa its incidence on the oil palm is not very high; deaths have been noted in Africa where leaves have been cut abnormally short and wounding of adjacent leaf bases has resulted. In America, incidence may well be higher. Deaths from *R. palmarum* attack have been noted in young plantings within the grove areas in Bahia, Brazil, and the pest is quite frequently encountered on oil palms in other parts of the continent. Its greatest importance in America may be as the vector for the nematode that causes red ring disease (Section 12.1.6.6).

Distribution and description: Species of these large weevils are to be found attacking palms in all parts of the tropics. The larvae tunnel into the crown and trunk, and the palm may be killed. As pests of the oil palm the distribution of the more important species is as follows:

<i>R. phoenicis</i>	Africa	
<i>R. palmarum</i>	America	Gru-gru beetle
<i>R. ferrugineus</i>	Asia	Red palm weevil, red-stripe weevil
<i>R. papuanus</i>	Celebes, New Guinea	

The larvae attain a length of some 5 cm and are ovoid or rounded, legless and yellowish-white, with small, brown heads. The last abdominal segment is flattened and has brown edges carrying bristles. The cocoons of the pupae, constructed of concentrically placed fibres, extend to 8 cm in length and 3.5 cm in breadth. The adults show distinct specific differences but are usually about 4–5 cm long and 2 cm broad. *Rhynchophorus phoenicis* is black with two narrow longitudinal dark

brown bands on the thorax; the wing cases have about a dozen longitudinal grooves. The underside of the body is light brown with diffuse black spots. *Rhynchophorus ferrugineus* is the common red palm weevil of the east; it is the species most commonly found in Sumatra and Malaysia (described under the synonym *R. schach*, and known as the red-stripe weevil). The oil palm has, however, proved far less liable to attack than the coconut palm. *Rhynchophorus ferrugineus* is rather variable in length (2–5 cm) and is red–brown with a few irregular black spots on the thorax. The variety known as *R. schach* is black with a longitudinal red–brown line down the centre of the thorax. The American species, *R. palmarum*, is entirely black with a velvety thorax, slightly prolonged at the base, and shiny grooved wing cases.

Life cycle and damage: *Rhynchophorus* weevils lay their eggs, which are 2–3 mm long, on cut or damaged surfaces of many palms. The eggs hatch in 3 days, and the larvae tunnel into the crown and trunk (Plate 12.8). The tissues around the growing point then begin to decay and the palm may be killed. The external symptoms of attack have been described as similar to those of *Fusarium* wilt: the leaves show a gradually increasing chlorosis and fracture in strong winds.

The larval stage lasts for about 2 months and pupation then occupies about 25 days, the larvae moving towards the periphery of the trunk to pupate. The whole life cycle lasts for less than 3 months. The weevil

more commonly breeds in the stumps of a felled palm field, newly cut stumps being preferred. *Oryctes* and *Rhynchophorus* species are often present in a plantation at the same time. Wounds made by *Oryctes* adults give a means of *Rhynchophorus* infection, while *Rhynchophorus* damage will provide conditions suitable for *Oryctes* larvae (Hartley, 1988; Zulnerlin and Fatah Ibrahim, 1999).

Control: Effective control of *Rhynchophorus* attack is not easy. In the first place, wounding of the palm must be avoided and the petioles must not be cut close to the trunk. Secondly, all dead or felled palms should be destroyed within the period of the beetle's life cycle. Measures for the control of *Oryctes* and other large beetles will help to reduce the incidence of *Rhynchophorus*. Mariau (1968) described various preventive and curative measures, including hooking the larvae from their tunnels with the aid of a wire.

The most promising approach is to trap the adult weevils. Initially, traps were baited with sugar-cane, pineapple, banana or palm tissue, but pheromone-baited traps are more effective. Oehlschlager *et al.* (1992) described the aggregation pheromone of *R. palmarum*. This compound, 'rhynchophorol', is released by male weevils, and attracts others of both sexes to the site of release. Pheromones have also been described for *R. phoenicis* (Gries *et al.*, 1993), *R. ferrugineus* (Hallett *et al.*, 1993) and various other species. Additional attractants include ethyl acetate and ethyl propionate, which are produced by damaged palm tissue, and the most effective traps were baited with the pheromone and palm tissue pieces (Gries *et al.*, 1994). The work on pheromones is summarised by Giblin-Davis *et al.* (1996). Chinchilla *et al.* (1995) described the use of pheromone-baited traps to capture *R. palmarum* and hence to control red ring disease.

Several parasites of *Rhynchophorus* species have been recorded. Moura *et al.* (1993) described a tachinid fly, *Paratheresia menezesi*, which parasitises *R. palmarum* in Brazil.

12.2.7 Root pests of mature palms

12.2.7.1 Oil palm root miner

The caterpillar of the moth *Sagalassa valida* (Brachodidae) has been found mining in the roots of oil palms in several South American countries including Colombia, Ecuador, Peru and Brazil. Up to 80% of the root system may be destroyed, and attacked palms may die.

Life cycle and damage: The female moth has a wing span of 2.1 cm, the male 1.8 cm. They live in the undergrowth and among the cut palm leaves in the interline, and their dull colour blends with that of the withered material. The position of egg-laying has not been



Plate 12.8 *Rhynchophorus palmarum* larva found in a 'spear rot' palm in Nicaragua. (B.J. Wood.)

observed, but it is presumed that it is in moist material such as lichens, mosses or humus at the base of the palm. The young larvae, which are no more than 1 mm long, penetrate the primary roots immediately after hatching, but can also move through the soil to attack roots some distance from the point of hatching. They at first eat the external part of the root, leaving the central cylinder intact; this partial destruction stimulates the production of new branch roots. Older larvae grow to 2 cm long, and cause complete destruction of the tissues of the roots in which they mine (Genty, 1973).

In areas of attack it has been noted that the number of caterpillars increases with the age of the palm, and in some palms 50–80% of the root system has been destroyed, including old and recent damage. Some attacked palms fall over (Genty, 1981). The amount of damage is highly variable, but tends to be greater on the edge of a plantation near the forest or near to rivers and streams.

Control: The possibility that sudden wither is associated with damage by this caterpillar has already been mentioned (Section 12.1.6.4). Genty (1977) considered that the extent of the damage done to the roots in itself justified treatment, and stated that a generalised yellowing of the leaves may be due solely to *Sagalassa*. He recommended routine checks by examination of one hole, 40 × 40 × 50 cm deep, at the foot of one palm/20 ha every 6 months. If more than 20% of the primary roots are attacked more intensive checks are done, and if 20% attack is still found then an insecticide should be applied around the bases of the palms. Treatment with endrin (now banned) was always followed by rapid regeneration of the root system.

12.2.8 Pests attacking fruit and bunches

In addition to the insects listed below, rats do considerable damage to fruit bunches (Section 12.3.1).

12.2.8.1 Oil palm bunch moth

Distribution: *Tirathaba rufivena* (Pyralidae: Galleriinae; formerly *T. mundella*) is widespread in Malaysia and Indonesia and can reach epidemic proportions, especially in young areas.

Life cycle and damage: Eggs are laid in the bunches, especially those overripe or rotten, and in inflorescences or bunches lying on the ground. Caterpillars bore into developing fruit or feed on the surface of ripening fruit. They are sometimes found tunnelling into the base of a spear leaf. They are light to dark brown and grow to 4 cm before pupating as dark brown pupae inside the bunch.

Control: Wood and Ng (1974) recommended spraying with endosulphan, but Basri Wahid *et al.* (1991) found that Thuricide (*B. thuringiensis*) was more effective than endosulphan, and cheaper than other effective insecticides. Two larval parasites have been identified: a chalcid wasp, *Antrocephalus* sp., and an ichneumon wasp, *Venturia palmaris*, of which the latter was more common and appeared to be the more promising for possible biological control (Ng, 1982).

12.2.8.2 Eupalamides cyparissias (Castiniidae): oil palm bunch miner

This pest (formerly known as *Castnia daedalus*) has done serious damage to bunches in Guyana, Surinam and Peru.

Life cycle and damage: The butterfly, which has a wing span of 17–21 cm, lays its eggs on unripe bunches. The larvae grow to 13 cm in a period of about 8 months, passing through 14 larval stages. The insect then pupates in the leaf bases for a period of 30 days. The larvae bore into the peduncles and bunches, causing rotting, and also into the stem. There is a high mortality from wasp and fly parasitism (Korytkowski and Ruiz, 1980).

Palms are attacked as soon as they start bearing, and provided harvesting is complete the larvae will be detected in the bunches and a measure of control obtained (Huguenot and Vera, 1981). Mariau and Huguenot (1983) described methods of estimating populations of larvae of different stages with the object of initiating control measures before the dangerous later larval stages are reached.

Control: Various control methods have been tried. Van Slobbe (1983) found injection of monocrotophos and carbofuran ineffective, but application of granular carbofuran in the spear region was successful. Huguenot and Vera (1981) recommended trichlorfon or carbaryl.

12.2.8.3 Demotispa neivai

Following the extended planting of the oil palm in Colombia, *Demotispa neivai* (previously *Pseudimatidium* or *Himatidium*) was reported from the Magdalena valley, and it has become a pest of the oil palm in all parts of South America, although not usually causing serious losses. A new species, *P. elaeicola*, was discovered on the Pacific coastal plain near Calima.

Life cycle and damage: The adult of *D. neivai* measures 5 × 3 mm and is at first white but rapidly becomes shiny brown with fine longitudinal lines along the wing cases. Single eggs are laid. The larvae are more flattened than the adult and their feet are short and withdrawn; they are at first translucent, later turning dull red, and

reach 7×4 mm. The pupae are brown and otherwise resemble the larvae. The insect is found on the under-surface of leaves, but the main point of attack is the fruit (Figueroa and van den Hove, 1967). Most damage is done by the larvae, which nibble the exocarp beginning at the apex. A fungus then develops at the point of attack and the exocarp becomes lignified and grey.

It has been estimated that a heavy attack leads to a loss of 7–9% of oil production, but that losses from the more usual mild attacks are, in spite of the alarming appearance of the bunches, negligible (Genty and Mariau, 1973). Young plantations are more vulnerable.

Control: The pupae of *D. neivai* are parasitised by *Tetrastichus* sp. and *Psychidosmiera* sp., but the amount of control exercised by these appears small. Ants are considered to play a more important role in limiting the population. Disbudding of young palms was recommended as a control measure by Mariau (1976b), if incidence exceeded 30%. Only if the attack becomes severe (a general attack of more than 70% of the palms, or more than 10% attacked heavily) is insecticide treatment thought necessary (Genty and Mariau, 1973).

12.3 MAMMALS AND BIRDS AS PESTS

12.3.1 Rats

Distribution: In the past, the most important mammalian pest of oil palms in Malaysia was *Rattus tiomanicus* (formerly *R. jalorensis*), the Malayan wood rat. Young plantings may be infested by the rice field rat, *R. argentiventer*, but *R. tiomanicus* is found in virtually all established oil palm plantations. The black, house or roof rat (*R. rattus diardii*) has also become an oil palm pest in parts of Malaysia (Wood *et al.*, 1988), and may now be almost as common as *R. tiomanicus*. Wood and Chung (1990) found that *R. r. diardii* occurred in areas where *R. tiomanicus* had developed warfarin resistance (see **Control**, below), and suggested that *R. r. diardii* could only compete with *R. tiomanicus* where the latter species had been weakened by the rapid evolution of resistance. Other rat species found in Asian oil palm fields are *R. exulans* and the bamboo rat, *Rhizomys sumatrensis*.

The genus *Rattus* only occurs in West Africa as introduced species in populated areas, but several other species are found in plantations. *Dasymys incomtus*, *Lemniscomys striatus*, *Lophuromys sikapusi* and *Uranomys ruddi* were recorded in the Ivory Coast by Bellier (1965) and Brédas *et al.* (1968).

A long-term study showed that the population of *R. tiomanicus* in a Malaysian plantation without rat

control fluctuated slowly between about 200 and 500 rats/ha (Wood, 1984). Wood and Liao (1984b) showed that *R. tiomanicus* was potentially capable of doubling in number every 46 days. However, in the absence of control measures, the actual population remained quite stable over long periods, rarely exceeding about 500 rats/ha. The reasons for this were not clear, but external environmental variables were deemed unlikely to be controlling factors, and predation appeared to depend on rat numbers, rather than the reverse. It seemed that there was some intraspecific mechanism, with population pressure affecting breeding success or survival of young rats. This needs to be remembered when considering possibilities for biological control by predators (see below).

Damage: Wood (1976b) estimated that a population of 300 rats/ha would consume about 480 kg of mesocarp/year, representing a loss of about 240 kg oil (Plate 12.9). This is about 5% of a good plantation yield, but the estimate ignored the loss of detached fruit. Taking account of detached fruit, Liao (1990) estimated total losses at up to 10% of production.

In an untreated area, palms showing fresh damage ranged from 0 to 39%, with an average over 10 years of 11% (Wood and Liao, 1984a). Wood (1976b) showed that there was a relationship between amount of fresh damage and rat population, and considered that 5% fresh damage indicated an economically damaging infestation. However, the correlation between amount of damage and rat population is not very strong, either for fresh damage or for detached fruit removed (Liao, 1990).

Young palms are sometimes attacked, probably mainly by *R. argentiventer*. If necessary, palms can be protected with wire-netting collars, as against the 'cutting grass' (see below), although the collar must be turned in at the top (Wood, 1968a).

Control: Poison baiting has been the main method of control, using anticoagulants, but there has been much interest in recent years in the possibility of biological control by owls.

Detailed instructions for baiting were given by Wood and Nicol (1972). Baits consisted of warfarin in cubes of maize and other ingredients, solidified with wax. The baiting procedure was a simple one: one bait per palm was distributed, with replacement of missing baits at 4-day intervals, until acceptance fell below 20%. With this system, rat populations could be reduced to negligible levels by four or five rounds of baiting. The recommendation was to repeat baiting every 6 months, although reinfestation could take over a year. Reinfestation appeared to be partly from outside, and partly



Plate 12.9 Fruit damaged by rats; the apical part of the mesocarp, and the kernel, have been eaten (from Corley, 2001).

from survivors (Wood, 1970). The former source is reduced by systematic baiting over large areas. Costs of control by baiting are typically equivalent to between 10 and 25% of the value of the lost oil (Wood, 1977; Chung and Balasubramaniam, 2000).

Warfarin baiting worked well for many years, but warfarin resistance eventually developed (Wood *et al.*, 1990) and is now widespread in Malaysia. Where resistance has developed, newer anticoagulants such as brodifacoum and bromadiolone have proved effective. With increasing labour costs, Chung and Balasubramaniam (2000) investigated alternatives to the replacement baiting method. They found that the replacement system remained the cheapest, even with high labour costs, but if sufficient labour was not available, then placing several baits per palm, or one large bait, in a single round was an effective alternative.

Recommendations for control of rats in Africa (IRHO, 1976) involved warfarin baiting on the same basis as described by Wood and Nicol (1972), together with wire-netting collars to protect young palms.

Biological control: In recent years there has been much interest in the barn owl, *Tyto alba*, for biological control of rats in oil palms in South-east Asia. Numbers of barn owls have increased enormously in Malaysia, following the expansion of the oil palm industry. In 1951, Glenister (1951) classified the species as 'very rare in Malaya', its having been recorded only three or four times. By the 1980s, Lenton (1985) described it as common. Lenton (1980) showed that numbers were limited by lack of nest sites, and designed a nest box;

these have been used successfully to encourage breeding in plantations. By 1989, Smal (1990) found one owl per 17 ha in one oil palm plantation, and one breeding pair per 8.5 ha in another.

Duckett (1982) summarised work by Lenton, showing that barn owls consumed large numbers of rats, which could comprise as much as 98% of their diet. It was calculated that a breeding pair of owls and their young would consume 1200–1500 rats/year (see Duckett and Karuppiyah, 1990). With one pair per 8.5 ha (see above), this is equivalent to about 160 rats/ha per year.

With an uncontrolled population of up to 600 rats/ha, there must be some doubt as to the degree of control that owls will exercise, and Wood (1985) noted that there is no well-documented example of a predator exercising continuing control over a vertebrate pest. Often, the predator population depends on the prey population, rather than vice versa; thus, snakes disappeared from oil palm plantations after rat control by intensive baiting started (Wood, 1985). We have already noted that rat populations stabilise at a certain level, despite having the potential to multiply exponentially. If a proportion of the population is removed by a predator, reproductive success may simply increase to restore the equilibrium population level. Alternatively, the population may stabilise at a lower level. Key questions then are: what is the equilibrium population level under owl predation, and is the amount of damage caused by that population economically acceptable?

Numerous authors have shown that owl numbers can be increased by providing nest boxes, but actual data on

control of rats are sparse, and those studies that have been done have not taken account of the large fluctuations in rat population that can occur in the absence of any control measures (Wood, 1984). Heru *et al.* (2000) estimated rat populations by trapping in plantations in Indonesia. Numbers trapped diminished from 100/ha in the year owls were introduced, to 20/ha 2 years later. They describe these figures as 'population density', but Smal (1990) estimated that in his study actual populations were about three times the numbers trapped. The relationship will, clearly, depend on the method and efficiency of trapping. However, if the rat population in Indonesian estates was reduced to as low as 60 rats/ha, that may be below the range of normal population fluctuations (Wood, 1984), suggesting that owls had an effect. In Malaysia, Smal (1990) found that rat numbers decreased after the owl population built up, but rat numbers also fell to a similar level in fields without nest boxes. This could have been because the owls hunt over a large range, well beyond the fields with nest boxes, but it could also have been a natural decline caused by some other factor. Chia *et al.* (1995) estimated populations of up to 400 rats/ha under owl predation in one estate, comparable to levels without control (see above).

Several comparisons of fresh damage levels before and after the introduction of owls have been made. It might be argued that the amount of damage is what matters, not the number of rats, but fresh damage is only a rough indicator of rat population, and is not the only damage done. Other rodents have been shown to change their habits when predators are about (e.g. Abramsky *et al.*, 1996), and it is possible that, when owls are present, rats spend more time in frond piles, consume more detached fruit and do less damage to bunches still on the palm. If feeding is mostly on detached fruit, then when considering the economics of rat control, one must ask whether such fruit would have been recovered if it had not been taken by rats (see Section 10.4).

Wood (1976b) considered that 5% fresh damage indicated an economically damaging population level. This has been interpreted as meaning that less than 5% damage is acceptable, but Wood used the 5% figure as an indication of a need for control by baiting. After baiting, damage should be reduced to zero, and will remain at that level for several months, so the average amount of damage over time would be well below 5%.

Duckett and Karupiah (1990) found fresh damage on 15–20% of palms before owls were established and on 8–15% after establishment. Smal (1990) found that fresh damage was reduced to about 3% after establishment of owls in one estate, but remained above 7% on

another. Ho and Teh (1997) found that damage in a 500 ha block of palms decreased to below 5% by the third year after establishment of owls, and remained low for the next 5 years, without baiting. Hoong H.K. (2000) found that, after the introduction of owls to Sabah, fresh damage in estates averaged 5%, compared with over 10% a decade earlier. In smallholdings, the comparable figures were 24% and 10%. In general, therefore, it appears that the amount of damage done when rats are controlled solely by owls may be less than without control, but is close to, and sometimes above, the threshold for baiting recommended by Wood (1976b). However, Adidharma (2002) claimed that fresh damage level was reduced from 30% to 0.14% after introduction of owls to a 14,000 ha plantation in Indonesia.

Smal (1990) and others have suggested that good control might be achieved by a combination of barn owls and limited baiting. If this is to be done, it is essential that owls eating poisoned, but still living rats should not be affected by the anticoagulant. There are various reports that owls are not affected by warfarin, but Lee (1995) found that warfarin and the second generation anticoagulants were all toxic to owls. The second generation anticoagulants were more toxic, but doses of warfarin taken by rats, and hence by owls, were higher. More work is needed if an integrated system using both owls and baiting is to function effectively, particularly on the choice of anticoagulant where warfarin resistance occurs.

Conclusion: Control of rats with anticoagulant baits is well established and cost-effective. However, as Chia *et al.* (1995) noted, the fact that planters will abandon a proven method in favour of barn owls, which are 'at best unproven', is a clear indication of the attraction of biological control. Owl populations are easily built up by provision of nest boxes, and they consume large numbers of rats. It appears that the equilibrium rat population in the presence of owls may be lower than in their absence, but the rats still do some damage. Smal (1990) calculated that construction of nest boxes was much cheaper than baiting, but noted that owls could not eliminate rats completely. In most studies, the amount of fresh damage has remained close to the 5% level that Wood (1976b) considered to indicate the need for baiting. For a proper comparison, the cost of this residual damage must be included in the costs of rat control by owls. Reliable trials would need to cover large areas, because of the hunting range of the owls, and would have to include an uncontrolled area, to show natural population fluctuations. Until such trials are done, the effectiveness and the economics of biological control of rats by owls remain uncertain.

12.3.2 Other mammals

The 'cutting grass', *Thryonomys swinderianus*, is common in Africa, and young areas planted near to the forest are particularly at risk from its devastating attacks. Protection against this pest using wire collars is described in Section 9.1.4.3. Porcupines (*Hystrix brachyura*) attack young palms on forest margins, gnawing through to the bud. Wire collars are not effective; zinc phosphide baits with palm oil in cassava root (Wood, 1968a) and chemical repellants (Chandrasekharan and Edmunds, 1976) have been employed.

Elephants have done great damage to young plantings in South-east Asia, systematically uprooting rows of newly planted seedlings. A ditch, 2.5 m deep and wide, may be an effective deterrent; though expensive, the cost is easily justified if there is a known risk of elephant incursion (Wood, 1977). Wild pigs damage or kill young palms, and monkeys occasionally pull up seedlings. Liaw (1983) described trapping methods used in Sabah for the control of these pests. In Indonesia, electric fences have proved effective for excluding pigs (Schmidt, 1986).

Squirrels (*Callosciurus* spp.) are occasionally troublesome in Asia, eating the mesocarp and sometimes attacking nursery plants.

12.3.3 Birds

The long-tailed parakeet (*Psittacula longicauda*), the blue-rumped parrot (*Psittinus cyanurus*) and the Malay lorikeet (*Loriculus galgulus*) have all been troublesome in Malaysia. Most destructive is the long-tailed parakeet, which feeds in flocks of up to 30 birds, carries away ripe fruit from the bunch and tends to scatter it about half-eaten. Such damage can be distinguished from rodent damage by the single beak groove in the fruit. The other species feed close to the bunch and do not scatter the fruit. Shooting is the only control known and with the long-tailed parakeet this does not seem to have been very effective (Wood, 1968a). However, with the expansion of the area under oil palms, most estates are now contiguous with other cultivated land, rather than adjacent to the parakeet's forest habitat, so their importance as a pest has diminished (B.J. Wood, pers. comm., 2001).

The American black vulture (*Coragyps atratus*) has become a serious pest in Brazil, Colombia, Honduras and elsewhere. In some countries these birds are protected by law as useful scavengers, and special permission must be obtained to shoot them. This course has been adopted in Colombia. In India, Dhileepan (1990) estimated that birds consumed up to 2.8 t FFB/ha per year. He suggested that cages could be used to protect bunches.

In West Africa the village weaver (*Ploceus cuculatus*) may be locally troublesome, stripping the leaflet laminae from a wide area to make nests in adjoining trees. It is usually necessary to fell the nesting trees to disperse the birds.

12.4 INSECT VECTORS OF DISEASES

As well as causing direct damage, some insects play an important role as vectors of disease. *Leptopharsa gibbicarina* (Hemiptera: Tingidae) appears to be the vector of *Pestalotiopsis* in leaf wither, and control of this insect has checked the spread of the disease (Section 12.1.5.2). A bug, *Recilia mica* (Delphacidae), has been implicated in the transmission of blast disease (Section 12.1.4). The weevils *Rhynchophorus palmarum* and *Metamasius hemipterus* are vectors of the nematode that causes red ring disease (Section 12.1.6.6). Two species of *Sogatella* (Homoptera: Delphacidae) have been shown to transmit a coconut disease similar to dry bud rot (Julia and Mariau, 1982).

Several insects have been associated with sudden wither (Section 12.1.6.4). *Sagalassa valida* was first suggested, then the hemipteran *Myndus crudus* (*Haplaxius pallidus*), but *Lincus lethifer* and *L. tumidifrons* (Hemiptera: Pentatomidae) now appear the most likely candidates.

12.5 PESTS OF OTHER COMPONENTS OF THE OIL PALM AGROECOSYSTEM

12.5.1 Pests attacking pollinating weevils

Since its introduction to oil palm-growing areas outside Africa, the pollinating weevil *Elaeidobius kamerunicus* (discussed further in Section 2.2.2.5) appears generally to have thrived. There have been occasional suggestions that poor pollination was due to pest or disease attack, but there is no convincing evidence for such effects. Liao (1985) reviewed what was known at that time, and little seems to have been added since.

The main predators on the weevil in the Far East are undoubtedly rats. These consume large numbers of larvae, destroying the old male inflorescences in the process, and Liao (1985) showed that rats grew more rapidly on a diet supplemented with weevil larvae. Basri Wahid and Halim Hassan (1985) considered that rat populations, and the amount of damage done, had increased since the introduction of the weevil. Chiu *et al.* (1985) estimated that up to 80% of weevil

larvae might be eaten by rats, but noted that the weevil population remained high enough to ensure good fruit set.

Kang and Zam (1982) detected, and eradicated, two species of parasitic nematodes in weevils imported to Malaysia. There have been more recent reports of weevils parasitised by nematodes in Malaysia, though (R.A. Syed, unpub.; Rao and Law, 1998), and Poinar *et al.* (2002) described a new species, *Elaeolenchus parthenonema*, which reproduces asexually and is an internal parasite of *E. kamerunicus*. Rao and Law showed that parasitised weevils had shorter life expectancy and lower reproductive rates than unparasitised. They considered that these effects, combined with low numbers of male inflorescences (the weevil breeding sites) during periods of high oil palm sex ratio, could lead to the poor fruit set which has sometimes been observed in parts of East Malaysia.

12.5.2 Pests attacking legume cover crops

Wood (1976a) and Liao (1979) reported that leaf-eating caterpillars, grasshoppers and cockchafers may do

considerable damage to legume cover crops. Perhaps equally importantly, though, Wood also noted the existence of 'chronic' pests, particularly the bug *Chauliops bisontula*. The occurrence of this pest in Malaysia, and the debilitation that it can cause, may explain why cover crop growth is often very weak in that environment. Liao (1979) reported a trial in which cover crop pests were controlled by insecticide spraying. The planted legume species made up a consistently greater proportion of the total ground cover biomass in the sprayed than in the unsprayed plots, indicating that the pests were reducing the vigour of the legumes. In the latter, more than half of the biomass consisted of weeds by 11 months after sowing.

Liao did not recommend insecticide spraying of the cover crop as a practical measure; spot spraying of weeds with herbicide is clearly more environmentally benign. However, the trial did help to explain why so much time and effort has to be spent on managing and maintaining the cover crop in Malaysia, whereas in most countries *Pueraria phaseoloides*, and the other leguminous species used, grow strongly in young palm plantings, easily suppressing most weeds.

Chapter 13

The Products of the Oil Palm and their Extraction

13.1 PALM OIL PRODUCTS AND THEIR CHEMICAL STRUCTURE

The properties and uses of, and extraction processes for, the main oil palm products, palm oil, palm kernel oil and palm kernel cake, all depend on their chemical structure, so this is briefly discussed here.

13.1.1 Palm oil composition

Palm oil is a lipid, meaning it will not dissolve in water, but will do so in a wide range of organic solvents. It is a mixture of triglycerides, compounds with the general composition shown in Fig. 13.1a. The groups labelled R are always long-chain fatty acids, with chains of varying numbers of carbon atoms (e.g. Fig. 13.1b). These are combined with glycerol (Fig. 13.1c) to form esters, in which the fatty acid residues can be the same or different. This esterification reaction can be reversed, to give glycerol and fatty acids, as explained below. Some of the fatty acids have only single chemical bonds between the carbon atoms, while other fatty acids have double bonds between carbon atoms in one, two or three positions. This difference is important for their chemistry, physical properties and nutritional value. Fatty acids or fats containing double bonds are called unsaturated, oleic acid, with one double bond (Fig. 13.1d), is known as monounsaturated, while linoleic acid, with two double bonds (Fig. 13.1f), is polyunsaturated.

The presence of at least one double bond introduces a complication, because a carbon atom can rotate easily around its single bond to its neighbour, but a double bond fixes the positions of the two carbons that it links. Such compounds can then occur in two different forms, called steric isomers, with a *cis* or a *trans* form (Fig. 13.1e), depending on the relative positions in space of the groups linked to them.

There are five important reactions that may be undergone by many or all fatty acid groups within a triglyceride molecule. The first is hydrolysis (Fig. 13.2a),

the reverse of esterification, so that the fat molecule is split, and the elements of water (H and OH) are added to the broken bonds, to produce glycerol and fatty acid(s). Measurement of the free fatty acid (FFA) content of palm oil is reviewed by Siew (2000a). When water is present, the reaction can be autocatalytic, or catalysed by some metals or by the enzyme lipase, which is widely found in living organisms and is also present in oil palm mesocarp. This hydrolysis can be undesirable, such as when palm oil still within the detached fruit begins to react, producing free FFA and diglycerides (Section 13.3.3), and it must be minimised during the whole extraction, purification and transport chain. Industrial hydrolysis is intentional, and involves reaction with an alkali such as sodium hydroxide. This produces glycerol, for which there are many uses, and soap, the sodium or potassium salt of a fatty acid.

The second reaction is oxidation, which is almost always undesirable. Free oxygen, especially in the presence of traces of metal and light, can attack the double bonds in an unsaturated fat or oil, forming hydroperoxides. Subsequently, these break down, with splitting of the carbon chain, to compounds that cause undesirable flavours or colours and reduce the value of the oil. The degree of peroxidation can be measured to give the peroxide value (PV), while the anisidine value (AV) gives a measure of the secondary breakdown (Section 13.4.5.2).

The third reaction is hydrogenation (Fig. 13.2b), by which a molecule of hydrogen attacks a double bond and produces a single bond, the hydrogen atoms adding to the two spare bonds. The reaction is catalysed by various metals. Hydrogenation allows the degree of unsaturation of an oil to be controlled, and this gives a great degree of flexibility to the industrial uses of oils (see Section 14.3.3.2). During hydrogenation there is significant isomerisation, so that some *cis*-type isomers may change to *trans*-type.

The fourth reaction is transesterification, in which the acids are rearranged among the three positions on the glycerol molecules, with the aid of a catalyst,

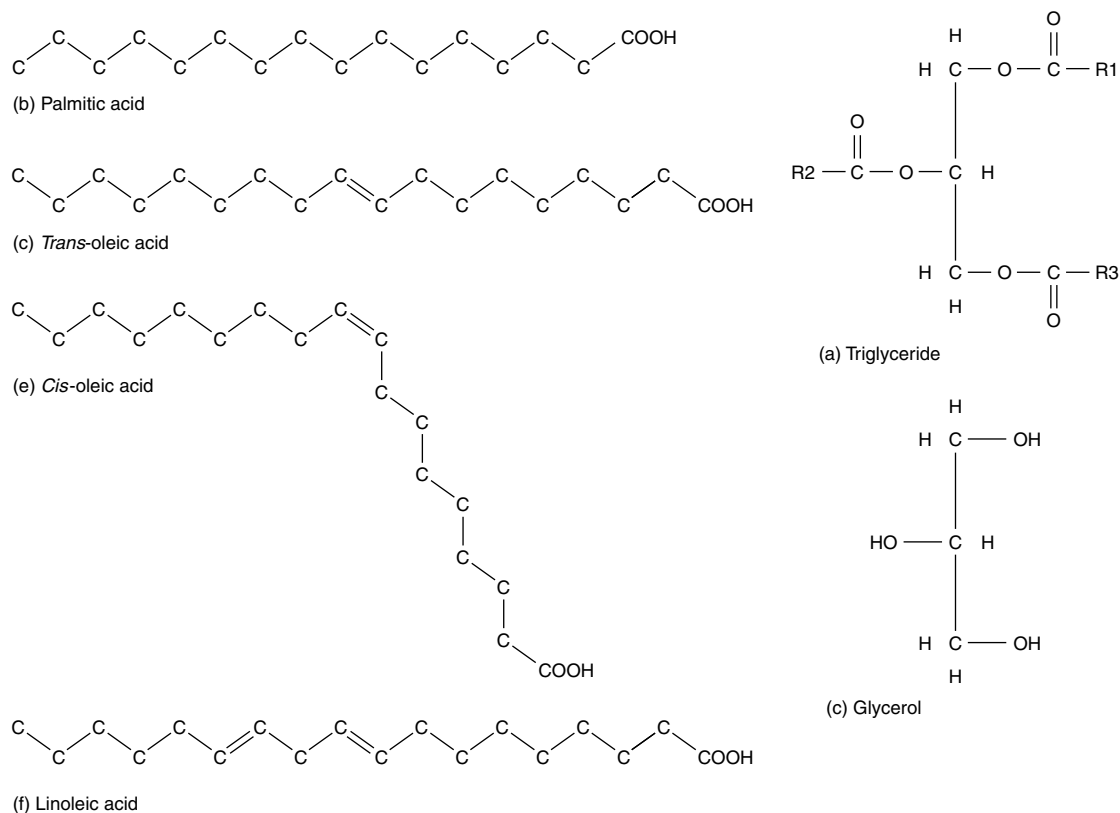


Fig. 13.1 Chemical structure of fatty acids, glycerol and triglycerides. Each carbon atom in a fatty acid chain carries two hydrogen atoms, or one in the case of double bonds (these are omitted for clarity).

producing a fat with different properties. Inter-esterification is similar, but involves redistribution of fatty acids between triglyceride molecules (see Section 14.3.3.3).

The fifth reaction is halogen addition, in which a molecule of iodine adds on to a double bond (Fig. 13.2d). This is the basis of the measurement of unsaturation, given by the iodine value (IV) (Siew, 2000a). High iodine values indicate a greater degree of unsaturation. Direct measurement of the iodine value is a long-established technique, but it can also be calculated from fatty acid composition measured by gas-liquid chromatography (GLC). A pure monounsaturated fat has an IV of 90, and a di-unsaturated fat 180. Thus, a fat with 40% oleic and 10% linoleic acids would have an IV of $(90 \times 0.4) + (180 \times 0.1) = 54$.

The physical properties of oils used in commerce are extremely important. Colloquially, 'fats' refers to solid material and 'oils' to liquids; this is not a scientific distinction, but the melting or softening points have to

be precisely specified for use in industrial processes and domestic usage; methods of measurement are discussed by Siew (2000a). This is a complex topic because palm oil (like other oils) is a mixture of many different triglycerides, with different fatty acids combined in different positions within the same molecule. There is consequently no single clear melting point of this mixture. At ambient temperature palm oil is usually a mixture of solid and liquid phases, the solid fat often settling out under supernatant oil. The physical fractionating of this mixture, to produce materials with different melting points and behaviour, is described in Chapter 14.

13.1.2 Fatty acid composition and structure

The fatty acid composition of typical Malaysian palm oil, and of some of the fractionated products, is shown in Table 13.1; much more detail is given by Tang (2000).

There is much variation from palm to palm in oil composition, and the possibility of changing composition by breeding is discussed in Section 5.3.7. A large biotechnology programme at the Malaysian Palm Oil Board (MPOB) aims to produce a genetically modified palm with a significantly increased proportion of unsaturated acids in the oil (see Section 6.6.2).

13.1.3 Triglyceride composition and structure

The different fatty acids occur in different triglyceride molecules in a fairly random way, although with a preponderance of unsaturated acids in the 2-position on the glycerol molecule (Table 13.2). The distribution of saturated or unsaturated acids in the 2-position may be important in relation to heart disease (Goh, 1998; see also Section 14.4). In samples from Congo, about 6% of triglycerides contained only saturated fatty acids, 48% two saturated to one unsaturated, 43% one

saturated to two unsaturated, and about 3% with only unsaturated fatty acids (Loncin and Jacobsberg, 1963). The comparable figures for Malaysian palm oil, from Jacobsberg (1975), were 8%, 49%, 36% and 7%.

Triglycerides have also been analysed in terms of total carbon atom number in the fatty acids. Mean figures for 100 Malaysian samples were: C46 0.7%, C48 8.5%, C50 42.9%, C52 39.0%, C54 8.6% and C56 0.5% (Tang, 2000).

13.1.4 Non-triglyceride constituents

All components of palm oil are oil soluble, and hence they are lipids. However, there are very small quantities of lipids that are not triglycerides, the importance of which is increasing (Goh, 1998). These include carotenes, tocopherols, sterols and terpenoids. These compounds are largely concentrated in the olein fraction of palm oil after fractionation. The main compounds are listed in Table 13.3.

Table 13.2 Triglyceride composition of Malaysian palm oil.
M: myristic; P: palmitic (but see below); S: stearic; O: oleic; L: linoleic

0 double bonds			1 double bond			2 double bonds			3 double bonds			4 double bonds		
FAs	%		FAs	%		FAs	%		FAs	%		FAs	%	
	1	2		1	2		1	2		1	2		1	2
PPP	4.8	9.0	POP	28.7	30.6	POO	19.6	21.5	POL	5.5	4.8	LOO	1.9	1.7
PSP	1.2	–	POS	4.7	–	PLP	6.9	9.3	PLO	4.8	6.5	PLL	1.4	1.5
Others	1.9	–	PPO	3.5	6.3	SOO	1.8	–	OOO	3.3	3.8	OLO	0.8	1.1
			MOP	0.9	–	PLS	1.2	–	Others	1.2	0.0	Others	1.0	0.1
			Others	1.9	0.0	PPL	0.9	1.4						
						Others	2.1	1.1						
Total	7.9	9.0	Total	39.7	36.9	Total	32.4	33.3	Total	14.8	15.1	Total	5.1	4.4

References: 1: Jacobsberg (1975); 2: Berger *et al.* (1978); in these figures, P includes all saturated fatty acids.

Table 13.3 Minor constituents of palm oil

Carotenes	%	Sterols	%	Tocopherols	%
Phytoene	1	β-Sitosterol	60	α-Tocopherol	21
β-Carotene	56	Campesterol	13	α-Tocotrienol	23
α-Carotene	35	Stigmasterol	24	γ-Tocotrienol	45
cis-α-Carotene	2	Cholesterol	3	δ-Tocotrienol	11
Lycopene	1				
Others	4				
Total (ppm)	500–700		250–620		600–1000

From Jalani and Rajanaidu (2000).

13.1.4.1 Carotenoids

These are strongly coloured, usually red or brown, compounds containing numerous alternating double bonds, some of which have the important property of splitting and forming vitamin A. They are thus known as pro-vitamin A compounds, with β -carotene being the most important (Sundram and Chandrasekharan, 2000). The concentration in palm oil is variable, but commercial oil will usually contain 500–600 ppm. The non-vitamin A precursor carotenoids are more stable than the precursors, and so may be able to maintain an antioxidant level for longer (Goh, 1998). The concentration of carotenes varies widely, as would be expected from the varied colours of oil palm fruits, and varies even within a bunch, and from bunch to bunch on the same palm. In general, Deli palms produce a less coloured oil than African palms do, and among the latter, oil from West Africa has the highest carotene content.

13.1.4.2 Other minor compounds

Compared with most of the edible vegetable oils, palm oil has a high level of tocotrienols and tocopherol, which are components of vitamin E (Table 13.3). These compounds are strong antioxidants, and have various helpful activities in relation to heart disease, e.g. inhibition of cholesterol plaques. The tocopherol concentration may be higher in plantation palm oil than in oil from grove palms (Hartley, 1988), perhaps because of more careful processing.

Sterols are usually present in palm oil to 300–500 ppm (Table 13.3). These sterols can be removed by physical refining, or left in the oil. They are believed to have anti-cholesterol activity, but their activity in the body is far from clear. Cholesterol is largely an animal product; palm oil contains only about 9 ppm (Tang, 2000).

13.2 NUT COMPOSITION

13.2.1 Kernel composition and structure

The structure of the nut, including the shell, is discussed in Section 2.2.1.1. The shell is important as a fuel in the extraction mill. The kernel is the true seed, and consists mostly of an oily, dull white endosperm. This is crushed to produce palm kernel oil, and a press cake that is used for animal feed. The average composition of palm kernels is 47–52% oil, 6–8% moisture, 7.5–9% protein, 23–24% extractable non-nitrogen

(mainly carbohydrates), 5% cellulose and 2% ash (Hartley, 1988). The moisture content is variable, as the kernels eventually reach an equilibrium with the relative humidity in which they are stored. Kernel cake, after extraction of the oil, is composed of about 48% carbohydrate, 5% residual oil, 19% proteins, 13% fibre, 4% ash and 11% water. It is a source of useful additional income, although it is far less important to the palm oil plantation than soyabean press cake is to a soyabean farmer (Section 14.2.2). It has a lower protein content than soya meal, and is less valuable to animal feed compounders for that reason. The protein is high in arginine and glutamic acid.

13.2.2 Kernel oil composition and chemical structure

Palm kernel oil (PKO) is similar in fatty acid composition to coconut oil, both being known as 'lauric oils' because of the high proportion of lauric acid (about 50% in PKO). It contains a smaller proportion of unsaturated fatty acids than palm oil, and consists predominantly of acids with shorter chain-lengths (Table 13.4). There are small quantities of C6 and C20 (caproic and arachidic) saturated acids, and of the unsaturated acids C16:1 and C18:3 (palmitoleic and linolenic). With the low content of unsaturated fatty acids the iodine value is only about 17. The melting range is also smaller than for palm oil, at 27–30°C, and the mean slip melting point is 27.3°C. Kernel oil is pale yellow, containing only about 7 ppm carotene (Yusoff, 2000).

13.3 OIL SYNTHESIS AND BREAKDOWN IN THE FRUIT

The physical changes accompanying ripening have been described in Chapters 2 and 10. Development of fats in the kernel precedes that in the mesocarp. Some data from the work of Crombie (1956) and Oo *et al.* (1986) are given in Table 13.5.

13.3.1 Kernel oil formation

At 8 weeks from pollination the content of the seed is liquid; by 10 weeks it becomes semi-gelatinous, and it is not really hard until the 15th week. At 10 weeks from pollination the amount of lipid is very small, consisting of membrane and other structural lipids; unsaturated fatty acids preponderate, as indicated by the iodine value of about 85 (Crombie, 1956). From this stage there

Table 13.4 Composition of palm kernel oil and fractionated products

Fatty acid	Palm kernel oil ^a		PK Olein ^b	PK Stearin ^b
	Turrell (1985)	Tang (2000)		
C8:0 Caprylic	3.3 (2.5–4.7)	4.2 (3.4–5.9)	4.3	1.9
C10:0 Capric	3.5 (2.8–4.5)	3.7 (3.3–4.4)	3.6	2.7
C12:0 Lauric	47.5 (43.6–51.4)	48.7 (46.3–51.1)	44.7	56.6
C14:0 Myristic	16.4 (15.3–17.2)	15.6 (14.3–16.8)	14.0	22.4
C16:0 Palmitic	8.5 (7.2–10.0)	7.5 (6.5–8.9)	8.3	8.0
C18:0 Stearic	2.4 (1.9–3.0)	1.8 (1.6–2.6)	2.3	1.8
C18:1 Oleic	15.3 (11.9–18.5)	14.8 (13.2–16.4)	19.2	5.6
C18:2 Linoleic	2.4 (1.4–3.3)	2.6 (2.2–3.4)	3.3	0.8
Iodine value	–	17.9 (16.2–19.2)	23.0	7.0

Turrell (1985): data for 54 samples from 16 countries.

Tang (2000): data for 118 samples of PKO, 52 samples of olein and 49 samples of stearin from Malaysia.

^aMean (range); ^bmean values.

Table 13.5 Changes in weight and composition of developing fruit

(a) Kernel

Weeks after pollination	Dry wt (g/nut)	Oil ^a (g/nut)	Saturated acids						Unsaturated acids	
			C6 + C8 (%)	C10 (%)	C12 (%)	C14 (%)	C16 (%)	C18 (%)	C18:1 (%)	C18:2 (%)
10	0.07	0.01	0.4	0.5	1.4	1.2	13.3	2.0	67.1	14.1
12	0.16	0.02	0.5	1.2	21.4	8.6	11.1	4.3	46.5	6.4
13	0.20	0.05	6.2	1.7	25.7	10.1	10.7	3.6	35.6	6.4
14	0.38	0.09	4.0	2.1	44.3	15.7	7.5	4.2	21.2	3.0
15	0.59	0.24	3.8	3.9	47.6	17.1	9.6	2.2	14.3	1.5
19	1.08	0.37	1.7	1.4	50.7	17.9	9.1	2.4	14.1	2.7
20	1.21	0.42	2.0	2.7	46.1	18.4	13.3	1.7	16.0	3.1

(b) Mesocarp

Weeks after pollination	Dry matter (%)	Oil ^a (% fresh weight)	Saturated acids					Unsaturated acids		
			C10 (%)	C12 (%)	C14 (%)	C16 (%)	C18 (%)	C18:1 (%)	C18:2 (%)	C18:3 (%)
8	12.2	0.09	4.2	3.1	1.0	27.5	4.4	22.2	24.0	13.6
12	11.6	0.14	1.4	1.5	1.0	27.0	4.5	22.7	23.9	18.0
16	18.5	6.4	0.1	1.7	0.4	35.2	5.4	42.6	13.9	0.8
20	62.5	47.8	0.4	5.5	1.1	40.8	5.0	35.9	11.3	0.0
Overripe	77.2	66.7	0.0	0.8	1.5	44.2	5.4	38.7	9.4	0.0

Kernel data from Crombie (1956); mesocarp from Oo *et al.* (1986).

^aIn the kernel analyses, weights are on a per nut basis. In mesocarp, oil is shown as per cent of dry weight.

is a slow accumulation of lipids until about the 12th to 13th week, when lipid formation becomes more rapid; the lipids laid down are largely saturated, principally lauric and myristic. The major accumulation occurs around the 14th to 16th week.

13.3.2 Palm oil formation

Fat formation in the mesocarp takes place late in fruit development (Crombie and Hardman, 1958; Thomas *et al.*, 1971). Up to about the 16th week after pollination, lipids

constitute less than 2% of the dry weight of the mesocarp, again consisting mainly of structural lipids. There is very little addition of any kind to the dry weight of the mesocarp from the 8th to the 16th week when, just prior to ripening, dry weight increases by 300–500% and fats come to constitute 70–75% of dry matter (Crombie and Hardman, 1958). During the long period of low oil content linoleic and linolenic acid levels are high; these are typical of membrane and chloroplast lipids. During the final weeks of ripening all of the fatty acids in combination increase, with oleic acid becoming second only to palmitic acid in quantity. The pathway of fatty acid synthesis is outlined in Section 6.6.2.1.

The process of oil accumulation in the fruit is important because of the need to determine the point at which harvesting is most profitable (Section 10.4.4). The very rapid build-up shortly before the fruits ripen and start to detach from the bunch means that quite small changes in harvesting procedure may have large effects on oil content. Once fruit start to detach, though, triglycerides start to break down, as discussed in the next section.

13.3.3 Lipase activity

It has long been assumed that palm mesocarp contains a highly active lipase, which releases FFA from triglycerides; the FFA content of crushed mesocarp may reach 30% within 5 min (Desassis, 1957). Tombs and Stubbs (1982) were unable to detect an endogenous lipase in surface-sterilised fruits, and suggested that all lipolytic activity was microbial, but other work has shown that there is an endogenous lipase (Abigor *et al.*, 1985; Henderson and Osborne, 1991). The latter authors suggested that the enzyme was inactivated by chilling, explaining why Tombs and Stubbs found no activity. However, Sambanthamurthi *et al.* (1995) showed that lipase activity could be inhibited by adding high levels of FFA, and suggested that the inhibition observed by Henderson and Osborne was due to feedback inhibition by FFA, and not to chilling. Similar experiments carried out by Henderson and Osborne (not reported in their paper) showed that the direct addition of these high levels of palmitic acid in the lipase assay could shift the pH sufficiently from the assay optimum for the result to appear as an FFA inhibition (D.J. Osborne, pers. comm., 2001). It is clear that further experimentation is still needed.

The function of the lipase remains uncertain. Henderson and Osborne (1991) found that activity developed at about the same time as oil synthesis commenced, and speculated that the lipase might play a part in triglyceride synthesis in the lipid-rich oleosomes of the

mesocarp, although the accepted pathway for triglyceride formation *in vivo* involves glycerol-acyltransferase enzymes (Sambanthamurthi *et al.*, 2000b). Lipases do not normally have a synthetic function in nature, although industrially they can operate synthetically under non-aqueous conditions (see Lortie, 1997, for review).

Hydrolysis of triglycerides does not occur in undamaged fruit, presumably because the lipase is compartmentalised within the cell and only comes into contact with the oil if cell membranes are damaged. The first stage is a partial hydrolysis, the products being FFA and diglycerides (glycerol with two fatty acids attached). The FFA can be removed by neutralisation, but the diglycerides remain, and have significant, and undesirable, effects on fractionation behaviour (see Section 14.3). It is therefore essential to minimise bruising or damaging of the fresh fruit before it reaches the mill, where the enzyme, together with any microbial lipases, is inactivated by sterilisation.

13.4 EXTRACTION OF PALM PRODUCTS

13.4.1 The extraction process

Most of the stages in the process are essentially the same, whether in a 60 t/h mill or a small-scale village process. The stages are as follows (Maycock, 1990) (see Fig. 13.3).

1. Bunch sterilisation with high pressure steam; this loosens the fruit from the bunch, and inactivates the endogenous lipase, and any micro-organisms, so that FFA build-up does not occur (Section 13.3.3).
2. Bunch stripping, to separate fruit from bunch stalk and spikelets.
3. Fruit digestion to pulverise and disrupt the mesocarp, with heating to aid oil extraction.
4. Pressing or other treatment of the digested fruit to extract the oil.
5. Separating, clarifying and drying the oil.
6. Separating nuts from fibre.
7. Nut drying, grading and cracking.
8. Separating kernels from shell.
9. Kernel drying and packing.

Mills are typically powered by steam turbines, and a generator driving electric motors of appropriate sizes for the different pieces of equipment. The steam comes from boilers fed with shell and fibre; boiler operation, discussed by Cooper (1983), is an important aspect of mill management. Wood and Corley (1993) estimated that the energy output of a plantation (182 GJ in the oil

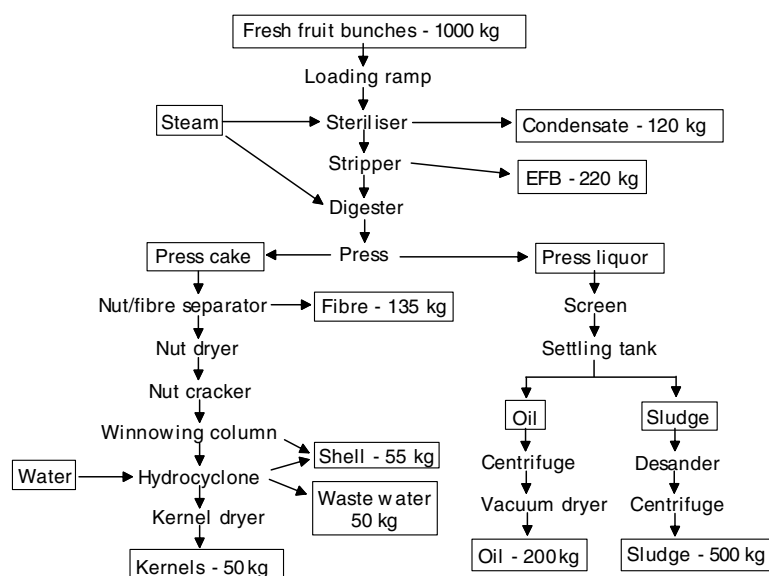


Fig. 13.3 Schematic flow diagram for palm oil and kernel extraction. Approximate mass of outputs shown, from 1 t of FFB, assuming 20% OER and 5% KER. (Based on Ma, 1999a, and Chan, 1999.)

and kernels from 20 t FFB/ha·yr) was over nine times the input energy (19.2 GJ/ha, of which fertilisers made up 59%, and fuel for transport 30%).

13.4.2 Extraction of palm oil and kernels by traditional methods

It is unlikely that any oil produced by these methods enters international trade now, but small-scale extraction still continues in Africa. A brief discussion follows; Hartley (1988) gives more detail. There are two methods, yielding 'soft oil' and 'hard oil'. For both methods, the fruit is allowed to ferment for a time (omitting stage 1, above). For soft oil, the fruit is then boiled for some hours and pounded into a pulp. The oil is separated by adding water and skimming it off; it is then heated to remove any residual water. The hard oil process is basically similar, except that initial fermentation is longer, there is no boiling, and the fermented fruit is trodden in a large container until it has formed a pulp. Again, water is added and the oil is skimmed off as it rises to the top. Both processes are inefficient, with 40–50% recovered by the soft oil process and 20–30% by the hard oil process (Maycock, 1990). The FFA values would be about 10% and 30–50%, respectively. It is hard to imagine procedures more at variance with modern plantation methods.

Various hand presses have been developed for village use; hand-operated centrifuges may also be used, with special sterilisers, or with boiling in drums as described above. The most successful press was a modified

wine-press, which could give extraction efficiencies of up to 70% under the best conditions. Systems developed around this type of press could deal with some 700–800 kg of bunches/day. The FFA content of oil produced in these systems was much lower than in the traditional methods. In 1959 hydraulic hand-presses came into use that were much more efficient, handling around 0.75 t of bunches/h in continuous operation, and extracting some 95% of the oil in the boiled pulp. These are discussed further in Section 13.4.4.

13.4.3 The palm oil mill

A modern palm oil mill or factory (Plate 13.1) consists of a number of sections, each performing one of the stages listed in Section 13.4.1. The development and operation of the mill is briefly outlined in the following sections; more detail of the early methods can be found in Hartley (1988). The first mechanised mills were constructed in Africa around 1909, in Cameroon and in Benin; the first one in Asia started in Sumatra in 1919. The modern mill design had developed before the 1970s, and recent developments in milling technology have been fairly minor (Southworth, 1976; Maycock, 1990; Menon, 2001).

13.4.3.1 Fruit reception

Fruit is normally delivered to a raised ramp. Tipping lorries or trailers deliver the fruit into sloping hoppers,



Plate 13.1 A large mill of 60 tonnes per hour capacity serving 8000 hectares in Malaysia.



Plate 13.2 Horizontal bunch sterilisers with bayonet-type doors. (Gebr. Stork & Co.)

with hydraulic doors controlling the loading of the fruit into steriliser cages. The effects of fruit handling on quality are discussed in Section 13.4.6.1. Fruit may be stored for several hours on the ramp, until the mill is ready to process it, thus providing a buffer between fruit transport, which is usually a daytime activity, and milling, which may be a 24 h process during the peak season.

13.4.3.2 Sterilisation

Some small mills use vertical sterilisers, but the horizontal steriliser is now standard. The steriliser consists

of a long, cylindrical pressure vessel, of about 1.8 m diameter, with rails running along the length of the interior (Plate 13.2). The fruit is loaded into 'cages', which are of approximately circular cross-section to fit inside the steriliser. These cages, each containing 1.5–2.5 t fruit, are pushed on the rails into the steriliser. Steriliser capacity depends on the length; a large steriliser would hold six or more cages, and a large mill would have several sterilisers. In some mills cages of up to 10 t capacity are used (Menon, 2001). Once the steriliser has been loaded and closed, steam is introduced. Pressure is built up to about 3 kg/cm^2 , which

corresponds to a temperature just above 130°C, and held there for about 1 h. As already mentioned, sterilisation serves two main purposes: it prevents FFA build-up in the oil, and it loosens the fruit on the bunch to facilitate stripping. Maycock (1990) also mentioned softening of the pericarp for easier digestion, and preconditioning of nuts to reduce breakage in the press. In some mills, detached fruit are sterilised separately. A period of 12–15 min is sufficient for such material, the shorter time greatly reducing oil losses.

'Hard bunches', in which stripping is incomplete, are often a problem, particularly where fruit set is very high, or where bunches have been harvested underripe. Stripping of hard bunches is improved by double or triple peak sterilising, in which pressure is released, and then built up again, but this tends to increase oil losses on empty bunches and in steriliser condensate (Section 13.4.5.2).

In recent years, there have been minor improvements in control mechanisms and safety devices; microprocessor control of sterilisation is well established in the industry. Sivasothy and Rohaya (2000) investigated a system of bunch crushing before sterilisation. Crushing meant that sterilisation could be done with low-pressure steam, giving the possibility of a continuous sterilisation process. Complete stripping was easy, and provided that heating immediately followed crushing, there was little increase in FFA content, but the mesocarp was not sufficiently soft for good digestion.

13.4.3.3 Stripping

The aim of stripping is to separate the fruits from the empty bunch, consisting of the stalk and spikelets. Small mills have used a 'beater' stripper, but the drum stripper is standard in modern mills; Chooi (1983) gave details. This consists of a horizontal drum, made of bars spaced so that fruits can fall through, but the bunches remain inside the drum. Cages of sterilised fruit are lifted and tipped into a bunch feeder; bunches are fed from this into one end of the stripper drum, either manually or automatically, sometimes with a feedback control from the digester. The drum rotates at about 22 rpm. In one design, the central shaft on which the drum rotated was eliminated; instead, the drum moved on rollers (Maycock, 1990). This reduced breakdowns, and adding beater arms increased stripping efficiency.

Empty fruit bunches (EFB) from the stripper are conveyed either to an incinerator or, more commonly now, to an EFB hopper prior to transport back to the

field for use as mulch (see Sections 10.1.3.2 and 11.7.2.1). The EFB conveyor is inspected continuously for hard or 'unstripped' bunches. These, which are usually more accurately described as partially stripped, are recycled for repeat sterilisation and stripping.

13.4.3.4 Digestion

Fruit from the stripper is carried by conveyor belt to the digester. The design of digesters has changed little over the years. There is a vertical cylinder, with rotating beater arms which pulverise the fruit, loosening the pulp from the nut. The mass of nuts and pulp is heated, before passing into the press, either by a heating jacket or by live steam injection. The latter is now the more common method (Maycock, 1990). Thorough digestion is critical for efficient pressing (Southworth, 1976).

13.4.3.5 Pressing

Oil extraction is the core of the mill operation, and press capacity normally determines the throughput of the mill. Centrifuges were used in many early mills, but hydraulic presses were introduced in the 1920s and gave greater extraction efficiencies (Hartley, 1988). Screw presses were first used in the 1950s (Maycock, 1990), and although there was much debate as to the relative merits of screw and hydraulic presses in the 1960s and early 1970s, screw presses are now universally used. The advantages of the screw press over the hydraulic press are (Maycock, 1990):

- continuous operation, and hence less labour required; the hydraulic press was a 'batch' process
- higher throughput, and hence less investment in buildings and machinery
- less power required for a given throughput
- nut/fibre separation is easier because of the lower oil content after pressing
- screw presses can handle a wide range of throughput rates.

A variety of different screw press designs is in use, with single screws or double screws, and throughputs of up to 20 t of fresh fruit bunches (FFB)/h (see Hartley, 1988, for more detail). The digested mixture of fibre, oil and nuts is forced through a perforated press cylinder by the rotation of the screw, or counter-rotating screws in the double screw press. Adjustable cones restrict the exit of the mass, so that pressure builds up in the press cylinder. In some designs, the pitch of the screw is gradually diminished, thus increasing the pressure.

Southworth (1983) gave information on factors affecting screw press performance.

Several alternatives to pressing have been investigated over the years. Maycock (1990) described the 'wet process' developed in Congo in the early part of the twentieth century. This involved the addition of hot water after digestion, to wash the oil out of the pulp. The method was further developed for small mills by Vandekerckhove of Belgium, who claimed 78–80% extraction using a fruit cooker and digester only, and 88–90% using a low-pressure (30 kg/cm²) piston press, followed by warm water washing in a counter-current wet digester (Cornelius, 1983). These extraction processes had capacities of 0.7–2 t of bunches/h.

The Drupalm[®] process, based on methods of olive oil extraction (Noel *et al.*, 1997a, b) involves crushing sterilised and stripped fruit including the nuts, in a hammer mill, followed by digestion, and separation of the oil in a three-phase decanter. The process is claimed to be cheaper both to install and to run than a conventional mill, and to have a higher extraction efficiency. It produces a mixture of palm oil and kernel oil, which would be a disadvantage for some uses. Because the kernel content of present-day *tenera* fruit is low, the oil contains only 3% lauric acid, but even that amount would be enough to change the fractionation behaviour of the oil. Noel *et al.* (1997b) claimed that the olein yield was higher than from crude palm oil (CPO), but accepted that the product might not be suitable for some processes. The loss of the higher value PKO is also a disadvantage, but the cost savings are said to offset this.

Solvent extraction has been investigated (British Patent 1104577, 1968; Everaerts and Lubis, 1976), and Southworth (1976) considered that higher extraction efficiency than with pressing should be possible, but it does not appear to have been attempted on a commercial scale. Health and safety aspects would have to be considered, depending on the solvent used. The solvent extraction of residual oil from fibre after normal pressing has been suggested, but this oil is known to contain a high proportion of carotenoids and non-oil components such as waxes (Olie and Tjeng, 1974), which would introduce bleaching problems.

13.4.3.6 Clarification, drying and storage

The crude oil from the press consists of a mixture of oil, water and other 'non-oily solids' (NOS: mainly dirt and fibre). Exact composition depends on how much water was added prior to pressing; Velayuthan and Chan (1983) quoted 66% oil, 24% water and 10% NOS, but

a survey of mills by Lim (1983) showed up to 50% water. Lim described the methods of separating of these components. Where the content of water and non-oily solids is low, simple physical settling is quite effective. In continuous settling tanks the oil/water mixture is fed into the middle of the tank, while separated oil is steadily removed from the top, and waste (sludge) from the bottom (Hartley, 1988). The oil and waste fractions are then centrifuged. More recently, decanters have been introduced, which can handle oil straight from the press, without the need for a settling tank (Kanamathy *et al.*, 1981; Roege *et al.*, 1983).

Finally, the oil must be dried, by the use of vapour extraction units or vacuum dryers, to prevent FFA formation by autocatalytic hydrolysis. Most mills in Asia achieve a water content of 0.1%, but Berger (1985) has suggested that it would be better to have a limit of 0.15%, as this would enhance the effect of antioxidants.

Storage is generally in welded steel tanks; the tanks contain heating coils, to prevent crystallisation and subsequent settling out of the solid phase. They may be filled with carbon dioxide or other inert gas above the oil, to prevent oxidation. The sensitivity of palm oil to higher temperatures is well established, and the temperature during storage and in transit is controlled to between 32 and 40°C, with loading and unloading temperatures between 50 and 55°C. Temperatures should be kept as low as possible, to minimise deterioration in quality during storage (Chong, 2000).

Berger (1985) published a draft code of practice for storage and transport, which in 1999 was adopted as the *Codex Alimentarius Code of practice for handling edible oils and fats* (Berger, 2000). In the latter paper, Berger described some of the contamination and quality deterioration which used to occur during shipping and pipe-line transfers in port, which the code of practice has eliminated.

13.4.3.7 Kernel handling

The cake coming from the presses consists of nuts and moist fibre, with some residual oil. To extract the kernels it is necessary to separate the nuts from the fibre, crack the nuts and separate the kernels from the cracked shells.

Fibre separation: This may be pneumatic, mechanical or hydraulic, but pneumatic fibre separators have become the standard in modern mills; Oh (1983) gives details. In the most commonly used type the fibre–nut mixture, partially dried, passes from a 'cake breaker' conveyor into a vertical airstream sufficient to carry the fibre upwards while the nuts fall into a smaller, lower rotating drum, where they are polished by friction. Some air also passes

through this drum, carrying any light particles upwards to join the main flow.

Purely mechanical fibre separators have been used for a long time, particularly in small mills where a low capital cost was imperative. One type consists of a screened drum which is rotated and allows the separated fibre to fall through the screen. A second type is a modification of a cotton ginning machine; a revolving shaft is fitted with studs which tease off the fibre. A third type has a rotary cage bounded by rollers, revolving in opposite directions in pairs, which remove the fibre to the outside of the cage but retain the nuts inside. Direct air separation columns are also used, in which the velocity of the upward current of unheated air which removes the fibre is adjustable.

Nut screening and cracking: The clean nuts may be dried in a nut silo or, if the drying during fibre separation has been sufficient, they may be conveyed straight to screens for grading by size before cracking. According to Maycock (1990), it is necessary to heat the nuts, to dry the kernels partially so that they shrink away from the shell, and then to cool them before cracking. Without this conditioning, kernel breakage is increased, and fragments of kernel adhere to the shell and are lost. If heating is excessive, though, kernel quality may suffer (Hartley, 1988).

In nut-cracking machines of the centrifugal type the nuts are fed through a central spindle, rotating at 1600–2200 rpm, and flung out against the wall of the cracker. A development has been the self-sorting nut-cracker which incorporates grading slots and pitching blades which grade the nuts and give them the correct speed for cracking; this makes prior nut screening unnecessary (Olie and Tjeng, 1974). Maycock (1990) mentioned the introduction of a ripple mill cracker, which has the advantage that prior nut conditioning is not required, and according to Menon (2001) this is now widely used.

Kernel and shell separation: In the early days the shell and kernel mixture was placed in a salt bath, of specific gravity such that the shells sank while the kernels floated, and could be skimmed off, washed and dried. Later a mixture of water and clay was found more suitable. Shell has a specific gravity of 1.3, and kernels 1.1 (Akubuo & Eje, 2002), and according to Hartley (1988), a clay bath SG of 1.17 was used. Maycock (1990) quoted SG figures of 1.17 for shell, 1.07 for kernels, and 1.12 for the clay bath.

Modern mills almost exclusively use hydrocyclones for separation, although the clay bath was cheaper. The mixture is fed into a rotating vortex of water, and the heavier shell particles settle, while the kernels are carried

off upwards. The shell is sent to the boiler house for fuel. The kernels should contain no more than 2.75% shell and other foreign matter (Turner & Gillbanks, 1974). Akubuo and Eje (2002) described a simple mechanical separator for use in small mills, but this gave kernels with about 20% shell, uncracked nuts and other impurities.

Kernel drying: Fresh kernels have a moisture content of about 20% and cannot be stored without deterioration. If the moisture content is much above 7%, hydrolysis of the oil in the kernel can proceed, both by autocatalytic hydrolysis and by lipolytic micro-organisms. Details of the latter are given by Hartley (1988), including some which are thermophilic and appear if a stack of kernel bags heats up to 50–60°C, as can happen occasionally. Hydrolysis is increased in proportion to the fraction of broken and damaged kernels. Drying is usually done in a silo: the fresh kernels are fed in at the top, warm air is blown upwards from below and dry kernels (7% moisture) are removed at the base. Menon (2001) described an experimental tray drier. The kernels may be steam-sterilised for 5–6 min before drying (Bek-Nielsen, 1969), and FFA of the kernel oil will then remain below 1% after storage for 6 months or more (Maycock, 1990).

Kernel oil extraction: In most mills, palm kernels are the final product, the crushing being done elsewhere (Section 13.5.2), but sometimes kernel oil is extracted in the mill, by pressing. This has the advantage of using the same power supply, derived from shell and fibre, as the rest of the mill.

13.4.4 Small-scale mills

For a long time palm oil production was considered either as a very large-scale business or as a small-scale peasant undertaking. For this reason there was much technical progress in the installation of very large mills and, at the same time, attention was given to providing for the non-mechanical needs of the small producer. However, in some parts of the world, notably America, the planting of small or medium-sized holdings of a few hundred hectares or less became common, and this engendered an interest in small mills of high efficiency. Such mills need to have a capacity of between 1 and 3 t of bunches/h and a low installation cost. The first small-scale or mini-mill was erected at the Central Experiment Station at Serdang, Malaysia, in the 1920s, and had both a small centrifuge and a small hydraulic press, but the first widely used such mill was the centrifuge-based 'Pioneer', which was introduced in Nigeria and other African countries in the 1940s. When wages rose steeply, these Pioneer mills became uneconomic in



Plate 13.3 Bunch stripper or thresher for the hand press mill.

comparison with small village curb-press businesses; Hartley (1988) gives details of the latter.

Small-scale mills now are of two kinds: they may be based on a hydraulic hand-press, or they may be fully mechanised but of low throughput and simple design. Mills of the first kind were developed at the Nigerian Institute for Oil Palm Research (NIFOR) (Nwanze, 1965), but Blaak (1979) found that the system was unpopular because of the high labour requirement for manual bunch stripping, pounding and reheating of the mashed fruit (Plates 13.3, 13.4). He constructed a village mill in Cameroon which allowed for the mechanisation of heavy work while retaining low-cost, simple apparatus. A small boiler provided steam for fruit sterilisation and nut drying, while diesel engines operated a digester, nutcracker and water pump. Production could reach 1 t of palm oil in an 8 h shift, equivalent to 0.625 t of *tenera* bunches/h. This type of mill is most suited to the traditional oil palm peasant agriculture of Africa and is unlikely to attract growers elsewhere. Some of its features were adopted by workers at the NIFOR/FAO (Food and Agriculture Organisation of the United Nations) Engineering and Development Unit in Nigeria (Hadcock, 1983; Badmus, 1993) with the same objectives in view. Baryeh (2001) studied the effects of processing conditions on palm oil yield from a hydraulic hand-press. The optimal duration of fruit cooking was 20 min, at 100°C. The yield was greatest with an extraction pressure of 25 MN/m², applied for up to 10 min.

The Kramer process developed in Ghana, described by Blaak (1989), involved bunch stripping and fruit cooking in the village, with hot fruit delivered by the farmer to a simple mill using a horizontal digester and hydraulic hand-presses. The press cake was returned to the farmer, who separated the nuts and dried the fibre



Plate 13.4 Pounding sterilised fruit.

before a second pressing. The oil produced was almost dry, so there was no liquid effluent from the process. The equipment was very cheap, but extraction efficiency was only about 82%.

Mills of the second kind with a capacity of 0.75–3 t/h have been installed in several parts of Africa and America. In the latter continent many of these mills have been locally designed and incorporate short horizontal bunch sterilisers with a compact rail system which enables the sterilised bunches to be moved easily from the sterilisers to the stripper (Plate 13.5). In many cases the mills have been constructed on a slope so that gravity can be used for moving the bunches to the sterilisers and to the strippers, and the fruit to the digesters.



Plate 13.5 Small cages, rails and weighing scales for short horizontal bunch sterilisers in a small, locally designed mill in Columbia.

Table 13.6 Typical oil losses

	Cause of loss						Total	Ref.
	Steriliser condensate	EFB	Hard bunches	Fibre	Sludge	Nuts		
Product as % FFB	14.7	18.9	2.62	13.3	42	—	—	1
Oil in product (%)	0.47	2.86	23.8	6.2	0.72	—	—	
Oil loss as % FFB	0.07	0.55	0.60	0.84	0.32	—	2.39	
Oil in product (%)	—	—	—	5.3	—	—	—	2a
Oil loss as % FFB	—	0.42	—	0.64	0.43	0.10	1.59	
Oil in product (%)	—	—	—	5.7	—	—	—	2b
Oil loss as % FFB	—	0.61	0.10	0.63	0.39	0.12	1.85	
Oil in product (%)	0.36	—	—	14.7	1.66	—	—	3
Oil loss as % FFB	0.07	—	—	0.9	0.68	—	—	

EFB: empty fruit bunch; FFB: fresh fruit bunch.

References: 1: Wood *et al.* (1985b) (data for seven 200 t batches of fruit, harvested to different ripeness standards; hard bunches recorded before recycling; figure = loss in fruit from such bunches if not recycled, measured after removal; bunch stalks of hard bunches included under EFB); 2: Velayuthan (1985) (a: mean for two mills, over 2 years before introduction of weevil; b: same mills for 2 years after introduction; hard bunches stated to be negligible before introduction; figure = losses persisting after recycling); 3: Sundaresan *et al.* (1990) (data from 1 t/h mini-mill; no figures given for loss on EFB).

Sundaresan *et al.* (1990) described a small mill constructed in India, with a capacity of 1 t FFB/h. This gave an oil extraction ratio (OER) of 19% with *tenera* fruit; some data for processing losses are given in Table 13.6.

In Nigeria, a horizontal digester and a single-screw press have been combined into one machine (Plate IIC, D), driven by a diesel engine, with a capacity of at least 1.3 t FFB/h. Owolarafe *et al.* (2002) compared the new machine with a hydraulic hand press: extraction

efficiency was greater (89% compared to 79% for the hand press), clarification was faster, and labour requirement was lower.

The main problem with mini-mills is ensuring adequate supervision and recording of both quantities and quality (Hartley, 1988). Weigh-bridges or other means of bunch weighing are often not provided as standard equipment, and the owners may not know either the extraction rates or efficiencies being obtained.

13.4.5 Mill operation

13.4.5.1 Siting of the mill

For an estate of 1000–2000 ha, some 4 ha of land will be needed for a mill and accompanying buildings. The following factors should be taken into account in siting a new mill.

- There must be a good supply of reasonably pure water. If necessary, a purification plant must be installed.
- The usual construction requirements for a large building must be met: the soil must have a reasonable bearing strength to prevent the need for extensive piling, and there should be no flood danger.
- The position should be central to the estate(s) from which fruit will be brought.
- There must be some permissible way to dispose of the effluent, with or without prior purification.
- With a suitable slope, and careful design, it may be possible to avoid the building of ramps and elevators.

13.4.5.2 Process control

Oil and kernel extraction ratios (OER and KER) are calculated from the tonnage of FFB coming into the mill, and the weights of oil and kernels produced. To manage the process, it is necessary to understand the possible errors in calculation of these ratios, and to measure the losses in the extraction process. These aspects are discussed below; more details are given by Velayuthan (1975, 1985), Velayuthan and Chan (1983) and Southworth (1977). Factory efficiency is calculated as:

$$\text{Oil produced} / (\text{Oil produced} + \text{Known losses})$$

Some of the sources of oil loss in the factory are regularly monitored, while others are assumed to be constant or not measured at all. Velayuthan and Chan (1983) grouped oil losses into 'known' (losses on fibre, bunch stalks, nuts and waste water), 'known but not recorded' (steriliser condensate, unstripped bunches, fruit spillage) and 'unknown' (errors in FFB weight or oil production, fraud). Some typical loss figures are shown in Table 13.6. Noel *et al.* (1997b) pointed out that the true efficiency of a mill was always lower than the 92–93% claimed, because not all losses were accounted for.

Measurement of FFB and oil: The measurement of incoming FFB depends on weigh-bridge accuracy. Oil is usually measured by volume in the daily production tank, volume being converted to weight, with a correction for temperature from standard tables. Provided that calibration errors are avoided, these measurements give accurate estimates of OER. Wood *et al.* (1987)

recommended comparing these figures with expected OER, calculated from bunch analysis data with allowance for known processing losses. Bunch analysis was used to estimate potential OER on representative batches of fruit from the various palm ages and planting material sources feeding into the mill. A daily figure for expected OER could then be calculated from the weights of different sources of fruit processed. This method was shown to give good prediction of actual OER, provided that harvesting was well controlled. Deviations below prediction would indicate processing faults or, more probably, harvesting or fruit-set problems. Rao *et al.* (2001) listed the changes in OER and KER that may follow from changes in fruit set or in harvesting standards. Possible processing losses are discussed below.

Steriliser waste or 'condensate': The quantity of steriliser waste can be measured, and samples, taken at regular intervals, analysed for oil; hence, the total quantity of oil lost over a period can be estimated. Sampling is usually infrequent, perhaps only weekly. This oil loss is usually small (Table 13.6), and the oil in the condensate is of poor quality, so in many mills the loss is excluded from the calculation of efficiency. However, the loss does vary depending on the sterilisation cycle (Velayuthan, 1985).

Bunch refuse: The weight of bunch refuse can be estimated by weighing a sample of the loads of EFB going to the incinerator or field, or measured directly with a weighing machine in the conveyer line. Sometimes it is not weighed, but assumed to be a constant fraction of incoming FFB. The EFB can be sampled and analysed for (a) unstripped fruit, and (b) oil absorbed by the stalk and empty spikelets. Chan K.S. (1977) found there was more oil in the stalks of overripe than under-ripe bunches.

The percentage of unstripped or 'hard' bunches is more difficult to measure reliably. Their number tended to increase in the Far East after the introduction of the pollinating weevil led to improved fruit set and more inner fruit in the bunch (see Section 4.4.7.1). The resulting milling problems were discussed in detail in a symposium (PORIM, 1985). Triple peak sterilisation, or splitting of bunches in half before sterilisation, was shown to reduce the incidence of unstripped bunches (Ismail *et al.*, 1985a; Velayuthan, 1985). Underripe harvesting also leads to an increase in unstripped bunches; as noted in Section 13.4.3.3, these should be recycled for further sterilisation. Provided that the recycling is efficient, the weight of bunches is easily determined, and if they are adequately stripped at the second attempt, the only loss should be a small increase in the oil loss in EFB (Wood *et al.*, 1985b). However, if inspection

of EFB on the conveyor is inefficient, not all bunches will be recycled. The loss if there is no recycling may be considerable (Table 13.6); in some batches of fruit, the oil loss in hard bunches, if not recycled, amounted to over 1% of FFB weight, or 5% of total oil (Wood *et al.*, 1987).

Fibre: The oil content of dry fibre is simple to estimate by solvent extraction; samples are perhaps best taken at the fibre cyclone. The total quantity of fibre must also be known. The simplest method of estimating this is to determine, by sampling, the ratio of dry fibre to nuts in the press cake; the total fibre is then calculated from the known tonnages of nuts produced (Velayuthan, 1975).

The figure of oil to dry fibre, being the largest among the accounted losses (Table 13.6) and this loss being obvious to the eye and touch, has received a great deal of attention. Gradual improvements in digestion and extraction methods have reduced the average figures over the years from nearly 20% oil to fibre to well under 6%, although losses in mini-mills may be higher (Sundaresan *et al.*, 1990).

Sludge: The tonnage of sludge (clarification waste) emitted for disposal and treatment is determined by using a basculator at the exit of the final sludge centrifuge or, if tanks are used, by counting the number filled and discharged. The ratio of sludge to bunches processed is then determined. Samples are analysed for oil and for 'solids not fat'. The same procedures can be applied to decanter cake, where a decanter is used. The losses in sludge are quite significant (Table 13.6).

Oil loss on nuts: This is easily estimated, provided that the weight of nuts is measured. The loss is usually small (Table 13.6).

Kernel extraction efficiency: Kernels may be lost in unstripped bunches, as small nuts remaining among the fibre, or with the shell. The first two can be estimated at the same time as oil losses on fibre are estimated. For the last, samples of shell must be analysed, and related to the total quantity of shell or nuts. Total losses are typically about 5% of total kernel production (Velayuthan, 1985).

13.4.5.3 Economics of a palm oil mill

The costs of milling are an important part of the total plantation operation. Davidson (1993) showed that productivity in the mill had increased from 33 t oil/worker per year in 1951 to 537 t/worker in 1991, representing an annual gain of 7.2%/year over 40 years. This arose from the replacement of centrifuges by screw presses, triple peak sterilisation, automation at the loading ramps, boilers and digesters, and a variety of other labour-saving changes. The increase in

productivity in the mill was greater than that in the field: in 1951, 17% of labour was employed in the mill, but by 1991, this was down to only 6%.

Mohd Arif and Mohd Nasir (1997) studied the costs of milling over 4 years in Malaysia. Increasing labour costs were offset by increasing throughput, so that cost per tonne of FFB remained stable. However, cost per tonne of oil increased, because of declining OER; the general decline in OER in Malaysia is discussed in Section 10.4. An important factor affecting profit per tonne of oil is the loss of oil and kernels during processing, discussed above (see also Menon, 2000).

13.4.6 Quality control

Good quality palm oil must have the following characteristics: low FFA content, low contamination with water and other impurities, and good bleachability. The standard tests for quality are reviewed by Siew (2000a). The characteristics interact; for example, a high water level is likely to lead to increased FFA. FFA can be removed, but a higher FFA level leads to a proportionately lower oil yield after neutralisation. This can be allowed for in the price, but a high FFA level can have a large effect on throughput of the refinery (Section 13.5.1). It also indicates a high diglyceride content, which affects the fractionation properties of the oil (Siew, 2000b). Oxidation affects the bleachability of the oil.

13.4.6.1 Free fatty acids

The FFA in bruised mesocarp increases rapidly (Section 13.3.3), so the first step towards avoiding high FFA is to handle the fruit carefully in both field and mill. Clegg (1973) classified the impacts to which a bunch may be subjected in harvesting, loading and unloading according to the resultant FFA increase. Each severe impact, such as from harvesting a tall palm or unloading onto the ramp, caused an FFA increase of about 0.2%. The most widely used ramp handling system, with tipping lorries and dropping from the ramp into steriliser cages, caused an overall increase between palm and steriliser of about 1.3% FFA. The best system was one where the steriliser cages were taken to the field and loaded immediately after harvesting, with no further handling, but this is now little used.

Once the bunch has been harvested, micro-organisms start to attack the fruit surface, through wounds or breaks on the surface, and the base of detached fruits. Most of these organisms have lipolytic activity, and will cause further FFA increase. Sterilisation kills

the micro-organisms and inactivates the endogenous lipase, but any delay in processing after the fruit has arrived at the mill will result in a higher FFA level. After extraction, the oil must be dried. In oil saturated with water (0.4% moisture), autocatalytic hydrolysis of triglycerides occurs, stimulated by FFA, but this reaction is negligible at 0.1% moisture (de Graaf, 1976; Berger, 1983; Chong, 2000).

The FFA limit is traditionally 5%; a premium may be paid for oil with lower FFA, although this has not been the case in recent years in Malaysia, where demand by the refining industry has outstripped supply. Special quality oils have sometimes been produced, where buyers were prepared to pay a suitable premium (Section 13.4.6.3). Hartley (1988) believed that attempts to produce such oils could be counterproductive, in that they encouraged managers to harvest underripe fruit and so lose production, but this may be justified if the premium paid for the special quality oil is large enough.

13.4.6.2 Oxidation and bleachability

The 'bleachability' of an oil sample can be measured directly as residual colour after bleaching (Olie, 1969). Bleachability depends on the carotene content, but is more affected by the oxidation state of the oil, the level of antioxidants and the contaminants present. The acceptable level of residual colour depends on the intended use for the oil, and is higher for margarines than for white fats or shortenings. A variety of tests for oxidation have been developed, of which the peroxide value (PV) is the most widely used. Benzidine or anisidine (AV) values may also be measured. The 'Totox' value is calculated as $AV + 2 \times PV$ (Jacobsberg and Jacqmain, 1973), but these authors considered that AV and absorbance of UV light at 233 nm gave an adequate measure of oxidation. If these were recorded, then PV did not give additional information.

Oxidation can occur at all stages during processing. Overripe and rotting fruit have poor bleachability (Olie, 1969). A moisture content above 0.2% suppresses oxidation during storage (Berger, 1983), but this conflicts with the requirement for low FFA (see above). High FFA also reduces bleachability (Parakh and Pathak, 2000). Copper and iron are catalysts for oxidation reactions, so contamination with these metals during processing and storage must be avoided. The copper content of the oil should be below 0.5 ppm, and iron content below 10 ppm. High FFA oil dissolves copper from brass fittings (Chong, 2000), and some mills use stainless-steel piping and fittings to minimise contamination.

Table 13.7 Special quality palm oils available in the past

Name	Source	Specifications
SPB (special prime bleachable)	Congo	FFA < 2.5%, good bleachability
SQ (special quality)	Malaysia	FFA < 2% at time of shipment
LOTOX (low total oxidation)	Malaysia	FFA < 2.5%, PV < 3 meq/kg, AV < 4 UV abs. at 233 nm < 1.5 Fe < 3 ppm, Cu < 0.2 ppm

From de Graaf (1976).

FFA: free fatty acids; PV: peroxide value; AV: anisidine value; UV abs.: ultraviolet absorbance.

High temperatures encourage oxidation, and should be avoided as far as is compatible with storage and shipping requirements (Section 13.4.3.6). Tocopherols play an important antioxidant role in palm oil (Jacobsberg *et al.*, 1978). Oxidation is a greater problem with refined oils, as the content of tocopherols is reduced during refining (Chong, 2000).

13.4.6.3 Technical standards for palm oil and palm kernels

In the past the standard for palm oil was defined in terms of FFA (below 5%), dirt and moisture. Special quality oils have been produced at various times (Table 13.7). There is now a wide range of palm oil-derived materials available in Malaysia, with standard specifications; most of these are listed in Table 14.2.

The FFA (expressed as lauric acid) in PKO is about 0.5% immediately after pressing, but this rises to 1.5% after drying, and after more prolonged storage up to anything between 2 and 10% owing to the action of microbial lipases (Loncin and Jacobsberg, 1964). Sterilisation of the kernels before pressing helps to control this process (Section 13.4.3.7), and may allow the FFA to be kept below 1.5% during storage for 6 months or more (Maycock, 1990). Typical contract specifications for PKO demand less than 5.5% FFA and 0.5% moisture and impurities (Hargreaves, 1985).

13.4.7 Extraction of minor components

Parakh and Pathak (2000) state that the value of the minor components, such as carotenes and tocopherols, is greater than the value of the palm oil itself.

Such statements can be misleading: if commercial extraction from palm oil were routine, supplies would be increased, and prices would be reduced accordingly. None the less, development work on extraction methods is clearly justified. Miyawaki (1998) described a commercial method of extracting the carotenes. This involves converting palm oil to fatty acid methyl esters. These can be differentially extracted into a methyl alcohol/water mixture, separating carotene from decolourised methyl esters. The carotene is then further purified and possibly fractionated. The methyl esters are used as feedstock for various oleochemical products.

13.4.8 Waste products

13.4.8.1 Liquid effluent

There are several sources of liquid effluent from a mill:

- condensate from bunch sterilising (0.6 t/t palm oil produced)
- the water phase or sludge from clarification centrifuges (up to 2.5 t/t palm oil)
- water from the hydrocyclone (0.25 t/t palm oil).

Palm oil mill effluent (POME) consists of a mixture of these liquid wastes. Kanapathy *et al.* (1981) described the use of a decanter–drier system, in which the water from the clarification stage was evaporated using exhaust

heat from the boiler, but in most mills the entire liquid waste is combined for disposal.

Most palm oil-producing countries now have regulations governing discharge of effluent from mills. The progressive increase in the stringency of Malaysia's limits for discharge of effluent into a watercourse is shown in Table 13.8. The limits for land application are rather less stringent, that for biological oxygen demand (BOD) being 5000 mg/l. To meet these standards, the treatment of the effluent is a vital part of the mill operations. The various systems available were reviewed by Ma (1999a).

First, there is separate settling treatment of steriliser condensate and clarifier waste, to remove residual oil; this is of poor quality and is used by the oleochemical industry. The mixed POME is a thick, brownish, colloidal slurry of water, oil and cellulosic residues from the bunches and fruit, the composition of which is shown in Table 11.28. This material is biodegraded by populations of micro-organisms, in processes that can be anaerobic, aerobic or facultative; often all three are applied sequentially in cleaning up POME. The anaerobic process produces methane, carbon dioxide and traces of hydrogen sulfide, while the aerobic process produces only carbon dioxide. Both also produce residual solid material. The anaerobic stage is a two-stage process, in which the first stage produces organic acids. These must be broken down by the second stage quickly enough to prevent the development of an extremely low pH.

Table 13.8 Malaysian limits for watercourse discharge for palm oil mill effluent

	Dates of application					
	1.7.78– 30.6.79	1.7.79– 30.6.80	1.7.80– 30.6.81	1.7.81– 30.6.82	1.7.82– 31.12.83	1.1.84 and thereafter
BOD (3-day, 30°C; mg/l)	5,000	2,000	1,000	500	250	100
COD (mg/l)	10,000	4,000	2,000	1,000	–	–
Total solids (mg/l)	4,000	2,500	2,000	1,500	–	–
Suspended solids (mg/l)	1,200	800	600	400	400	400
Oil and grease (mg/l)	150	100	75	50	50	50
Ammoniacal nitrogen (mg/l)	25	15	15	10	150 ^a	150 ^a
Total nitrogen (mg/l)	200	100	75	50	300 ^a	200 ^a
pH	5.0–9.0	5.0–9.0	5.0–9.0	5.0–9.0	5.0–9.0	5.0–9.0
Temperature (°C)	45	45	45	45	45	45 ^a

Based on *Environmental Quality (Prescribed premises) (Crude palm oil) Regulations, 1977*, Department of Environment, Malaysia (from Mariana, 1999).

^aValue of filtered sample.

BOD: biological oxygen demand; COD: chemical oxygen demand.

The great majority of mills use the ponding system (Fig. 13.4). This is a very simple system, in which pumps to move the liquid forward are the only machinery (gravity may also be used, depending on site layout). It needs careful control, to prevent a sticky scum forming on top of the liquid and solids accumulating on the bottom, thus decreasing the effective volume of the pond. This system loses the biogas methane that is produced. Trials have been done using large steel tanks as closed digesters, in which biogas is collected and recirculated to ensure good mixing, and these allow collection and use of the biogas. A 1200 t/day mill can produce 20,000 m³ biogas/day, with an energy content of 5300 kcal/m³ (Quah and Gillies, 1981). However, it appears that costs are not competitive with those for fossil fuel at present, and so far as we are aware, the process is not being used on a significant scale.

13.4.8.2 Solid wastes

The solid wastes from a mill may include any of the following.

- *Empty fruit bunches*: In the past, this material was incinerated, and the ash used as fertiliser. However, as a result of a combination of clean air regulations

(Mariana, 1999) and realisation of the value of organic matter as mulch, it is now much more commonly returned to the field *in toto* (Gurmit *et al.*, 1999b). Other possible uses for this material are discussed in Section 13.6.1.

- *Surplus shell and fibre, not required as fuel*: Where there is a surplus, most mills will use the fibre as fuel, as this is harder to dispose of in other ways. Husain *et al.* (2002) described fuel briquettes made from fibre and shell, with starch as a binder. These had a density of 1100–1200 kg/m³, and a calorific value of 16.4 MJ/kg. Shell makes a good road metal for estate roads. It can also be used to produce activated carbon (Cheah and Hoi, 1999), but so far as we know this is not being done on an industrial scale.
- *Decanter cake*: This is most commonly returned to the field to recycle the nutrients that it contains. It may also be dried, for easier handling. Gurmit and Toh (2000) describe a system in which inorganic fertilisers are mixed with the cake before drying to make granulated ‘compound’ fertilisers. The dried cake may also be used as animal feed.
- *Solids from effluent ponds*: Regular desludging of ponds is recommended (Ma, 1999a), with the solids being recycled to the field.

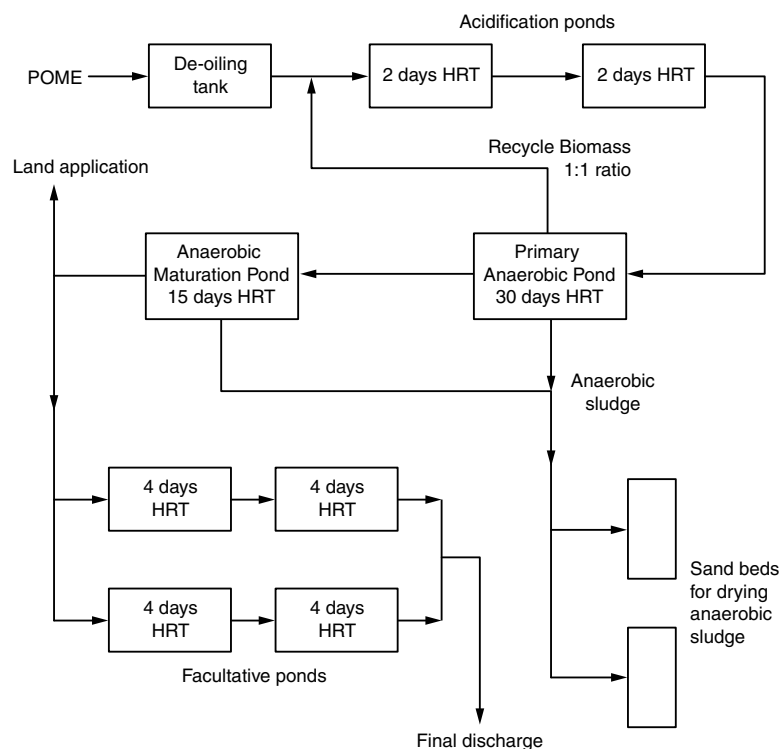


Fig. 13.4 Schematic flow diagram for a ponding system for effluent treatment. HRT: hydraulic retention time. (From Ma, 1999a.)

13.5 PROCESSING OF OIL PALM PRODUCTS

Until the 1970s, refining and fractionation of palm oil was done in consuming countries, but in 1974 the first refineries opened in Malaysia, and less than 5% of Malaysia's production is now exported as crude oil (Maycock, 1990). Both refineries and fractionation facilities are now often grouped with large oil mill complexes. Refining is described below, and fractionation in Chapter 14.

13.5.1 Refining of palm oil

Refining is necessary to remove FFA, coloured pigments, phospholipids and other compounds that could affect appearance, flavour or functionality in end-product manufacture. Much refining is now done in producing countries, particularly in Malaysia, but there remains a considerable international trade in CPO.

Initially, alkali refining was used to remove FFA, with the acids extracted into alkali. Later, physical refining was introduced, and is the standard method now: in 1989, 95% of Malaysia's refining capacity used the physical method (Maycock, 1990). According to Yusoff (2000), alkali refining is two to three times more expensive. The following stages are involved in physical refining.

1. Treatment with 0.1–0.4% phosphoric acid at 90–110°C, to remove gums (degumming).
2. Treatment with 1–2% bleaching earth, held at 95°C for 30 min, under a vacuum of 20–25 mmHg, to remove pigments (bleaching).
3. Cooling to 60–70°C, and filtering to remove bleaching earth.
4. Steam-stripping at 240–270°C, under a vacuum of 2–5 mmHg, to remove FFA and volatile compounds (neutralising and deodorising).

The final product is described as 'refined, bleached, deodorised' (RBD) palm oil. Parakh and Pathak (2000) and Yusoff (2000) give details of recent technical improvements in this core process in the oil palm industry. The individual processes may be separated, and a range of products exists, such as neutralised palm oil, neutralised and bleached palm oil, and so on (see Table 14.2). Refined, deodorised (RD) palm oil, produced by a mild alkali process and retaining about 70% of the carotenoids (Yusoff, 2000), is now a standard grade, sold for its content of provitamin A.

Refinery throughput is reduced by the need to handle high FFA oils (Parakh and Pathak, 2000); an increase of FFA from 4 to 6.5% can reduce the throughput to 60%

of the original level if the end-product quality is to be maintained.

13.5.2 Processing of kernels

PKO is extracted from the kernels, leaving palm kernel cake (Section 13.2.1). Where the end-products are for export, as in countries such as Malaysia which produce a large volume, this 'crushing' is usually done in large, centralised plants, often near to a port. This gives economies of scale and easy bulk handling. Such large crushing plants usually use solvent (hexane) extraction, which gives kernel cake with about 2% oil. In smaller markets, where the PKO and cake are for local consumption, crushing may be done in the mill on the plantation. In such cases, screw presses are usually used; these give a cake with 8–13% residual oil, but are cheaper and simpler to operate than the solvent process (J.H. Clendon, pers. comm., 2001).

The quality of the oil and cake is very dependent on the quality of the kernels from which they come. The cake should be light coloured, and contain normal levels of proteins and constituent amino acids. Cake quality is reduced if the kernels are contaminated with shell.

Good quality PKO has low FFA, is a light yellow colour and should be easily bleached to a colourless state. Sterilisation of the kernels before pressing is necessary to prevent FFA build-up in the oil, but any heating, either during sterilisation or under inappropriate storage conditions, will cause some discoloration. This browning of the kernels affects the colour of both the cake and the oil after pressing.

13.6 OTHER OIL PALM PRODUCTS

There is a continuing drive to obtain more high-value products from the oil palm, without losing or damaging the markets for the traditional products. Products from the oils are discussed in Chapter 14. Many papers at PORIM conferences have been devoted to potential uses for by-products or co-products; some of the more interesting ones are listed below (see also Section 13.4.8.2).

13.6.1 Biomass

Mature oil palms will produce 20–30 t/ha per year of above-ground biomass, or plant dry matter (see Section 4.1.2). The main sources that can potentially be removed and used, in addition to the oil and kernels,

are EFB and pruned leaves, and the trunks and crowns of palms that are felled before replanting. The total dry matter production over a 25-year planting cycle will be well over 400 t/ha. The idea of using some of this material for new products has been considered for at least 20 years (see papers quoted by references here). At present, the oil palm ecosystem works on the basis of recycling most of these biomass materials (see Section 11.7), but there is enough experience of fields in which EFB has not been returned to conclude that exporting this material would be acceptable, despite the undoubted advantages to the palms of recycling. (EFB is almost never recycled into fertiliser trial areas, unless it is one of the treatments in the trial.) There is much less experience of removing all three sources of biomass, and this would need field experiments over several years to test its sustainability (Fairhurst and Mutert, 1997). Khalid *et al.* (1996a) detected no effect on yield from removal of petioles over a 6-year period, but Hashim and Yeow (1987) found that FFB yield, leaf nitrogen, phosphorus and potassium contents, leaf area and petiole cross-section were all depressed by 5 years of complete frond removal. Results will depend on the extent to which nutrients removed are replaced by additional fertiliser inputs.

13.6.1.1 Paper and board

Much of the available biomass has no large-scale inherent strength or structural properties, so must be broken up. It can then be used for paper or board (H. Kamarudin *et al.*, 1999), and many tests have been conducted of various methods of pulping oil palm trunks, oil palm fronds and EFB. Kamarudin *et al.* (1999) concluded that the most promising material was EFB, although a paper mill of reasonable capacity would need the output from 40 average oil mills. All of these would have to be within 150 km for the transport costs to be acceptable, so siting of the paper mill would need care. The situation is analogous to that in western Europe, where repeated attempts have been made to use straw for paper making. So far, these have been defeated by the transport costs needed to gather large tonnages of straw together, and the fact that present paper mills are organised to use softwood and see little advantage in undergoing major change. It is to be hoped that the Malaysian experience will be more profitable.

13.6.1.2 Structural and building uses

Another main use of biomass is as structural and building materials. Parts of the oil palm trunk can be used for

plywood, and as the basis for blockboard and fibreboard (MDF). Trunks, fronds and EFB can be used as material for one- and three-layer particle board, bonded with a resin. The denser material from the base of the trunk, treated with a suitable resin, can be used to make furniture. Several of these uses have been tested successfully (Koh *et al.*, 1999), in the sense that usable materials have been produced. Most uses need a good-sized factory to give commercial economies of scale, and it is not clear yet whether the capital costs will be justified.

13.6.1.3 Microbial processing

It is theoretically possible to convert biomass into many other useful materials by microbiological processing (Cheah and Hoi, 1999). The use as a material for growing mushrooms seems feasible. Single-cell protein manufacture seems less promising, on the basis that it has been tried many times and rarely been found to be economic. As with so many processes of this nature, they are possible, but not profitable. The profitable discoveries are rare, but they must certainly be searched for. It is essential that there is a hard-headed and economically experienced manager in charge of such programmes.

13.6.1.4 Traditional uses

In some parts of Africa, annual pruning is done to provide leaves for thatching, wall construction and other purposes. Sly (1968) mentions the use of rachises as multipurpose poles, rope made from strips of midrib twisted together and brooms made from bunches of midribs. The alkaline ash from incinerated EFB is traditionally used for soap making (Taiwo and Osinwo, 2001).

13.6.2 Palm wine

In Africa, palm wine is quite a valuable and well-known product where it can be produced within easy range of a market. Details can be found in Hartley (1988). The sap is obtained by tapping a male inflorescence, or alternatively by tapping the growing point of a felled palm, after which the sap ferments naturally. In Nigeria, at one time, the income from tapping male inflorescences for palm wine was said to be greater than that from the palm oil and palm kernels (Hartley, 1988). Felling the palm simply for the wine is clearly very wasteful, but where felling for replanting is in progress it causes no difficulty. In parts of West Africa a significant 'cottage industry' has developed, and the income from selling felled palms for tapping can cover a considerable part

of replanting costs. Cheyns *et al.* (2001) quoted a figure of over US\$500/ha.

13.6.3 Animal feed

Dried mill effluent has a protein level of about 12%, and extensive trials were done in Malaysia in the 1970s on using POME for animal feed. The product has a rather low energy content and is not very digestible, and most ruminants cannot tolerate a very high proportion in the diet (Hutagalung *et al.*, 1982). Dalzell (1977, 1978) found that water buffalo, which are well adapted to a very coarse diet, could take no more than one-third of the diet as undried effluent. However, if the water content was reduced to 75%, effluent could provide up to 85% of daily nutrient requirement, and effluent plus press fibre up to 95%. Energy needed to dry partially the effluent was a limitation, but this might be overcome with a decanter, which can produce an effluent with only 70% moisture (Roegel *et al.*, 1983). The decanter-drier system of Kanapathy *et al.* (1981) produced a product with 10% moisture, and trials of this as animal feed were mentioned by Gurmit and Toh (2000).

Other by-products have been suggested as a basis for animal feed. Goats can be fed successfully on a diet with 50% fresh or ensiled leaflets (Dahlan *et al.*, 2000). Cattle can be raised on a diet of pelleted leaflets, palm kernel cake and mill effluent, supplemented with tapioca waste and rice bran (Kawamoto *et al.*, 2001). Other products (EFB, press fibre) have a value only as roughage, equivalent to rice straw, with negligible protein content. One possibility is to break up the tissues so that the cellulosic materials with little feed value are used for particle board, while the parenchymatous tissues are used for animal feed.

A difficulty that appears to have discouraged work on effluent as animal feed is the irregularity of supply, which fluctuates seasonally in line with the FFB input to the mill. The material cannot be stored, so the animal herd must be matched to the lowest output. The surplus at peak periods then has to be disposed of in the normal way. However, if the material is regarded as a source of nutrients, rather than simply as a waste product, then a system might be devised which combined animal feeding with recycling to the field of both dung and peak season decanter solids.

Chapter 14

Marketing, Economics, End Use and Human Health

Our intention in this chapter is to give a broad but brief outline of the fate of palm oil and palm kernel oil after they leave the palm oil mill or the refinery, which we hope will be useful to growers and agricultural researchers. We have not attempted to give a comprehensive review of current research on these subjects, and readers requiring detailed information will have to consult more specialised works.

14.1 PALM OIL MARKETING

Palm oil is grown for two quite distinct types of market: oil for local consumption, and oil as an exportable commodity. These two types of market are considered separately below.

14.1.1 International trade

As noted in Section 1.4, larger volumes of palm oil enter international trade than of any other vegetable oil. As a result, a sophisticated market for the commodity has developed.

Historically, palm oil was imported to Europe from Africa, and later Indonesia, and was traded after arrival in Europe. The Liverpool price was the standard up to World War II; thereafter, the Rotterdam price became the standard. Voituriez (1998) studied monthly prices over 180 years, from 1818 to 1998. The Rotterdam price is a 'spot' price, for immediate delivery of 'physical' batches of oil. However, both producers and buyers of commodities wish to be able to fix future prices, and thus to reduce their exposure to market fluctuations. Forward selling and futures are the two main mechanisms for this. Forward selling is the simpler approach: producer and buyer agree a contract for delivery at a fixed price and on a specified date in the future. The price agreed will depend in part on the current spot price, and on expectations for future supply and demand. Problems can arise if a large movement in the spot price occurs before delivery on the forward contract. For example, if

a producer sells forward, and a drought then causes a production shortfall and a rise in the spot price, he may have to buy in palm oil to cover the shortfall on the contract, at a price higher than he has agreed to sell it for. Conversely, if the price falls, the buyer will be at a disadvantage to his competitors who did not buy forward.

A 'future' is essentially a forward contract, but the contract itself is a tradable commodity, rather than an agreement between a particular buyer and seller. The price of the future is only a fraction (typically 10%) of the value of the oil it represents. This 'gearing' encourages speculators to come into the market, providing liquidity and assuming risks which would otherwise be borne by buyers or producers. In the above example, the producer selling forward could 'hedge' (insure against the risk) by buying a matching future. If prices rise because of a production shortfall, the value of the future will also rise, covering the loss he would otherwise have made.

Trading in palm oil futures on the Kuala Lumpur Commodity Exchange (KLCE, now known as the Commodity and Monetary Exchange of Malaysia) commenced in 1980. The intentions were to provide 'an efficient price discovery mechanism' and to provide hedging facilities against market fluctuations (Fatimah Arshad and Zainal Abidin, 1993). Previously, palm oil traders had relied on soya bean futures for hedging. The early performance of KLCE crude palm oil (CPO) futures was reviewed by Shahabudin (1993). By 1995, the total volume traded on the KLCE was equivalent to over 13 million tonnes (Nasir Amiruddin and Abdullah, 2000).

A crucial factor in the market is the fact that palm oil is seen largely as a general-purpose oil, and for many uses is interchangeable with other oils, particularly soya and rapeseed (known as canola in North America). Thus, the palm oil and soya bean oil prices are highly correlated; for example, the correlation of monthly prices between 1984 and 1988 was 0.93 (Bastin, 1990). Soya bean is an annual crop (as are most other vegetable oils), so total production may vary considerably from

year to year, depending on the area planted. This is affected by price expectations at the time of sowing, and by competing demands for land for other crops. For example, high prices for maize will lead to reduced soya bean planting. There is a further complication, in that oil is essentially a by-product of soya bean growing. Soya bean meal constitutes about 80% of the weight of the bean, so the demand for meal for animal feed has a large influence on soya bean planting, and thus indirectly on the palm oil price. The weather in the mid-western soya bean-growing area of the USA will affect expectations of soya bean yields, and hence future palm oil prices.

14.1.2 Local consumption

In large parts of Africa palm oil is the main traditional cooking oil. Much of the oil for this market comes from semi-wild groves or village palms, but plantations in Africa also market CPO for immediate local consumption. Palm oil is also grown industrially for local manufacture of margarine, soap and other products. This is important in countries where production costs are too high for competitive exports, but where shipping costs are also high, so that imports would be more expensive than local production.

14.1.3 Factors causing distortions of markets

A range of factors can cause distortions of international trade in vegetable oils (and many other commodities). Most aspects were reviewed in the 1989 *PORIM Conference on Chemistry, Technology and Marketing*, but the situation is continuously changing. We will not go into detail, but will briefly list the most important factors relevant to palm oil trade, and their effects on the free market or world price.

- Subsidies, support prices, deficiency payments and intervention buying can encourage production of oils regardless of demand, and in areas where production might otherwise be uneconomic. Thus, surpluses may accumulate, and prices will be depressed when these are 'dumped' on the market, and may be depressed in anticipation of such dumping. Such government support is susceptible to political pressures.
- Import duties are charged by many countries, often to protect a local industry from competition by lower cost producers. This will tend to depress prices outside the tariff barrier, although the effect

will be small unless a very large industry, such as rapeseed in Europe, is being protected. High tariffs also encourage smuggling, which may negate the intended benefit to local producers.

- Export duties are charged by some producing countries, sometimes with exemptions for certain products. Malaysia has an export duty on CPO and lower rates of duty on refined products; the structure is very complex, and was described by Nasir Amiruddin and Abdullah (2000). The intention when the duty was introduced was to encourage local refining. The measure was very successful, and little CPO is now exported; in 1997, CPO made up less than 0.5% of Malaysia's total palm oil exports (Nasir Amiruddin and Abdullah, 2000). However, a demand for CPO still exists (now met largely from Indonesia), and for some years there was a thriving business outside Malaysia reconstituting 'crude palm oil' from olein and stearin, often with an excess of the cheaper stearin fraction.
- In some countries a marketing board was established, which set a fixed price for commodities. The stated aim was usually to stabilise prices, but the price set was sometimes well below the world price, with the result that growers could not produce economically, and stopped producing or moved into other crops. In the 1960s, while Malaysian companies were converting rubber plantations to oil palm, some oil palm plantations in Nigeria were converted to rubber, because the palm oil price was controlled, but not the rubber price.

With so many factors in play, future palm oil prices are almost impossible to predict, and even past price changes may be difficult to explain. One observer may attribute a price drop to excess palm oil stocks overhanging the market, and expected high yields because of good weather last year in Malaysia, while another refers to favourable weather in the mid-west of the USA and a strong demand for soya meal. However, as noted in Section 1.4.2.1, average palm oil prices, in common with most commodities, have been declining steadily for several decades. There is much fluctuation around the trend line, but since the early 1960s, prices have declined by an average of about 3% per year (Fry, 1998). In the long term, demand for vegetable oils will continue to increase: fat consumption tends to increase as incomes rise, and a large part of the world's population still consumes less fat per annum than the 12 kg per person recommended by the World Health Organisation (WHO). It should not be thought that this will break the trend of declining prices, though. Consumption has

increased enormously since the 1950s, owing to both increasing population and increasing wealth, but this has not stopped prices from falling.

14.2 PRODUCTION COSTS

14.2.1 Palm oil production costs

Costs of palm oil production vary greatly from one producing country to another, for two main reasons. First, yields vary, mainly because of the effects of climate (see Chapter 3); some costs are essentially constant per hectare, and thus are inversely proportional to yield when expressed on a per tonne basis. Secondly, palm oil growing is labour intensive, and labour costs differ widely between different countries, as does labour productivity. Labour requirements for the main operations are given in Chapters 8–10. Differences in labour use between countries are partly a result of differences in labour cost; where this is high, there is an incentive to increase productivity and reduce numbers.

Davidson (1993) analysed changes in production costs over 40 years in Malaysia. Overall, production cost per tonne of oil had decreased at an annual rate of 2.6% (after adjustment for inflation). This had kept pace with the declining palm oil price, allowing the business to remain profitable. The cost reduction was attributable in part to a four-fold yield increase, from both breeding and agronomic improvements (see Section 5.5.2), and in part to increased labour productivity. In 1951 there was one worker per 4 ha, producing 5.7 t of palm oil per year; by 1991, one worker covered 7.5 ha, and produced 30 t of palm oil.

There have been few direct comparisons of production costs between countries; precise figures vary with

wages rates and exchange rates, and also with accounting practices, and numerous assumptions have to be made. Some cost comparisons are summarised in Table 14.1, but these can only indicate general trends. Production costs in the Far East are clearly much lower than in Africa, because of the higher yields in the former. Costs in Indonesia are in general lower than in Malaysia, because of the lower wage costs in Indonesia. Labour use is least in Malaysia, because high costs have driven producers towards mechanisation.

14.2.2 Production costs of competing oils

The important influence on the palm oil market of other vegetable oils, which are more or less interchangeable with palm oil, has already been mentioned. True production costs are difficult to arrive at, particularly for soya bean, because the main product of that crop is the meal, not the oil. Stringfellow (2000) estimated that during the 1990s, the oil varied between 30 and 44% of the total soya bean product value.

In 1998, Stringfellow (2000) estimated that soya bean oil production costs in the USA, Brazil and Argentina were 2.2–3 times palm oil costs in Malaysia, and 2.7–4.6 times those in Indonesia. However, the Malaysian and Indonesian currencies were unusually weak in 1998, which would have distorted this comparison. Fry (1996) estimated that soya bean oil production costs from 1985 to 1992 were about 50% higher than Malaysian and Indonesian palm oil costs. In 1991, Davidson (1993) estimated that the cost of rapeseed oil production in Europe was about 3.2 times the cost of palm oil production in Malaysia, but Bastin (1990) gave figures of 1.5–2.6 times.

Palm oil is much more productive per unit land area than other oil crops, and at present that leads to highly

Table 14.1 Palm oil production cost comparisons between countries. All figures expressed as percentages of the reference country, usually Indonesia

Year	Malaysia	Indonesia	Africa	America	Other	Ref.
1998	100–120	67–100	–	138 Colombia	–	1
1998	132	100	–	–	–	2
1993–94	116	100	–	–	–	2
1992	170	100	336 Ivory Coast	247 Colombia	197 PNG	3
1989	155–179	100	390 Ivory Coast	–	–	4
			520 Cameroon	–	–	4

References: 1: Stringfellow (2000), Fedepalma (2000); 2: Fry (1998); 3: Gray and Siggs (1994); 4: Nasir Amiruddin and Basiron (1993).

competitive production costs. In the long term, though, costs will increase as labour expectations rise, and the high labour requirement for palm oil production must become a major disadvantage. Gan and Ho (1994) estimated that the palm oil industry could absorb an expected four-fold increase in cost per man-day between then and 2020, but the discrepancy in labour requirements between palm oil and other oils is much greater than a factor of four. Stringfellow (2000) calculated that it takes 0.07 man-days to harvest 1 t of soya bean oil, compared with 2 man-days for 1 t of palm oil, 30 times more. In Brazil, Fearnside (2001) estimated that there was one worker to 160–200 ha of soya beans, whereas for oil palm a typical figure is less than 10 ha per worker. Mechanisation is discussed elsewhere (particularly in Section 10.2), but it should be clear that further major improvements in labour productivity will be needed if palm oil is to remain competitive with other oils in the long term.

Fry (2002) pointed out that soya bean and rapeseed yields had been increasing faster over the previous 25 years (1.3% and 2.4% per annum respectively) than oil palm yield (0.9% per annum). He predicted that, unless labour productivity could be improved, by 2010 Malaysian palm oil might have a higher production cost than Brazilian and Argentinian soya bean oil.

14.3 USES OF PALM OIL AND PALM KERNEL OIL

Oils and fats serve a number of functions in cooking, summarised by Berger (1996a). In frying, the high temperature and intimate contact between the oil and the food result in rapid cooking. In baking pastry, the fat prevents the hydration and toughening of wheat proteins, while in cakes the incorporation of air bubbles in the fat gives the desired crumb structure.

14.3.1 Importance of oil composition

The melting and crystallisation behaviour of fats is critical in determining their suitability for particular uses. These characteristics depend on the fatty acid and triglyceride composition (see Section 13.1 for palm oil composition data). The crystallisation behaviour of palm oil was reviewed by Timms (1990). The measurement of these characteristics is complicated, and modern physical methods may be used, including differential scanning calorimetry, nuclear magnetic resonance and X-ray techniques (Siew, 2000a).

Because fats are a mixture of different triglycerides, and not single, pure compounds, they have a melting range, rather than a specific melting point. When a figure for a melting point is quoted, it usually refers to 'slip point', the temperature at which melting starts. The melting behaviour of some palm oil products is shown in Fig. 14.1.

The importance of the melting range is exemplified by cocoa butter. This contains over 70% solid fat at temperatures up to 20°C, but melts over a relatively narrow range and has no solid fat content above 35°C. In contrast, palm oil has only 50% solid fat at 10°C, 25% at 20°C and 10% at 30°C. The narrow melting range of cocoa butter, slightly below body temperature, means that it is solid at room temperature, but melts rapidly in the mouth, giving it a pleasant, fresh and non-greasy taste. The melting behaviour of cocoa butter results from its high content of triglycerides with oleic acid in the middle position, and saturated acids at the 1- and 3-positions: Xu (2000) quoted figures of 35% POS (palmitic–oleic–stearic), 26% SOS and 16% POP triglycerides. Similar triglycerides are found in some other oils (illipe, shea), which are used in cocoa butter replacers. Palm oil 'midfraction' contains a significant proportion of POP triglycerides; these are sufficiently similar to SOS and POS that palm midfraction is the main component of some cocoa butter equivalents (Berger, 1996a). Figure 14.1 shows the relatively narrow melting range of palm midfraction, compared with CPO or palm stearin.

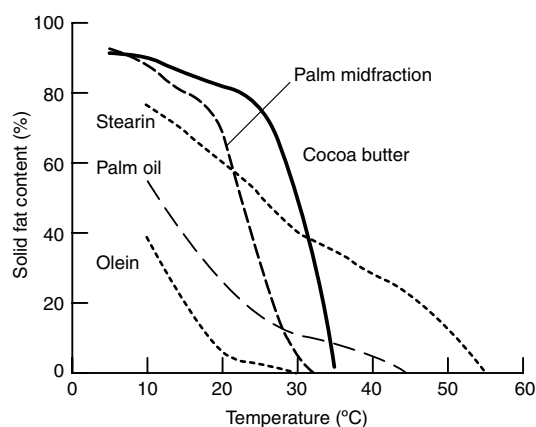


Fig. 14.1 Solid fat content of oils and fats at different temperatures. The relatively narrow melting ranges of palm midfraction and cocoa butter can be seen. Smooth curves are drawn through data points from Tang (2000) (CPO, olein and stearin) and Jinap *et al.* (2000) (cocoa butter and palm midfraction).

Margarine consists of an emulsion of water droplets in oil, stabilised by solid fat crystals. The solid fat content of a packet margarine will be about 40% at 5°C, but for a tub margarine, to be spreadable immediately it is removed from the refrigerator, this figure should be below 20% (Berger, 1996a). Vanaspati, a vegetable alternative to ghee (clarified butter, widely used in India, Pakistan and elsewhere), has a characteristic granular crystalline structure, with minimum free oil content at room temperature, but a melting point no higher than 37–38°C.

In much of West Africa, CPO is the traditional cooking oil; it has a characteristic 'nutty' flavour (Kuntom *et al.*, 1989), which is much appreciated. For many markets, though, a cooking oil should look clear at room temperature. Palm olein, with a cloud point (the temperature at which visible crystallisation starts) just below 10°C, meets this requirement in the tropics, but not in temperate climates. The liquid oils such as soya bean, corn and rapeseed have cloud points below 0°C, as do blends of these oils with up to 40 or 50% palm olein (Berger, 1996a).

The facts that a major part of the vegetable oils market is taken by liquid oils, and that palm olein generally fetches higher prices than stearin, have encouraged the view that oil palm breeders should aim for more liquid oils. The possibility of changes through breeding or biotechnology are discussed in Sections 5.5.7 and

6.6.2, but two important points may be noted here. First, if oil composition is changed by breeding, the oil must be sold as a speciality product, not as standard palm oil (with added costs for keeping it separate). Palm oil users' processes are finely tuned to oil with a standard composition, and oil with a higher iodine value than normal will not give the expected results in fractionation and product formulation. The second point is that a significant proportion of liquid vegetable oil is hydrogenated or otherwise processed to increase its solid fat content (see Section 14.4 for the health implications of this), so simply looking at the proportion of the commodity market taken by liquid oils may be misleading. Palm oil or palm stearin can substitute for these hydrogenated oils in some products.

14.3.2 Range of palm oil and kernel oil products

With the development of a refining industry in producing countries, particularly Malaysia, a wide range of palm oil products is now available on the market. Refining is discussed in Section 13.5.1, and some of the palm products exported from Malaysia are listed in Table 14.2. As noted above, Malaysia exports very little crude palm oil. The main supplier of that commodity to world markets is Indonesia. Although almost all palm oil will be refined before it reaches the consumer,

Table 14.2 Palm oil products and Malaysian standard specifications

Product	FFA (max. %)	Moisture, impurities (max. %)	IV	Colour ^a	MP (°C)
Crude palm oil	5	–	–	–	–
Neutralised palm oil	0.25	0.1	50–55	–	33–39
Neutralised and bleached palm oil	0.25	0.1	50–55	max. 20 red	33–39
RBD palm oil	0.1	0.1	50–55	max. 3 or 6 red	33–39
Crude palm olein	5	0.1	min. 56	–	max. 24
Neutralised palm olein	0.25	0.1	min. 56	–	max. 24
Neutralised and bleached palm olein	0.25	0.1	min. 56	max. 20 red	max. 24
RBD palm olein	0.1	0.1	min. 56	max. 3 or 6 red	max. 24
Double-fractionated palm olein	0.1	0.1	min. 60	max. 3 red	max. 19
Crude palm stearin	5	0.25	max. 48	–	min. 44
Neutralised palm stearin	0.25	0.15	max. 48	–	min. 44
Neutralised and bleached palm stearin	0.25	0.15	max. 48	max. 20 red	min. 44
RBD palm stearin	0.25	0.15	max. 48	max. 3 or 6 red	min. 44
Palm acid oil	min. 50	3	–	–	–
Palm fatty acid distillate	min. 70	1	–	–	–

From Berger (1996a).

^a Colour measured with Lovibond Tintometer, 5% cell.

FFA: free fatty acids; IV: iodine value; MP: melting point; RBD: refined, bleached, deodorised.

a significant demand for CPO persists in international trade. One reason for this is that refining can disguise problems with quality. If free fatty acid (FFA) content is high, the oil will also contain a high level of diglycerides. The FFA is removed in neutralisation, but the diglycerides from a high FFA oil will remain, and have an influence on fractionation and crystallisation properties (Siew, 2000b). There is no quick and easy method for measuring diglyceride content, so for specialised uses, manufacturers may prefer to buy low FFA CPO to be sure of quality, and undertake the refining themselves, even though the Malaysian export duty structure is such that a refined product might be cheaper.

Special quality CPO has been produced by various countries (see Section 13.4.6.3). As Table 14.2 shows, the standard for CPO is no more than 5% FFA, but for many years there has been an excess of refining capacity in Malaysia, and the resulting competition for CPO supplies has meant that quality aspects have not been emphasised.

14.3.3 Processing of vegetable oils

Vegetable oils may be processed in various ways, to give products with different solid fat content, melting range and crystallisation behaviour from the original raw materials. The main processes are fractionation, hydrogenation and interesterification.

14.3.3.1 Fractionation

A vegetable oil is a mixture of several different triglycerides, and those containing a high proportion of saturated fatty acids have higher melting points than those with unsaturated fatty acids. High- and low-melting triglycerides can be separated by partial crystallisation, to give olein (liquid, more unsaturated) and stearin (solid, more saturated) fractions. After the first separation of olein and stearin, further fractionations can be done to give such products as palm midfraction and 'super olein' or second olein. It should be noted that the terms olein and stearin refer to the liquid and solid fractions obtained after fractionation. They do not describe fatty acid composition; a palm olein will have increased oleic acid, because that is the main unsaturated fatty acid, but it will still contain most of the triglycerides in the original oil, although in changed proportions. Tri-olein is the term for a triglyceride in which all three positions on the glycerol molecule are occupied by oleic acid.

The main triglycerides tend to crystallise out in the following order during fractionation: PPS, PPP, SOS, POS, PPL, PPO, OOS, POO, PLO, OOO and OOL, where O is oleic, L is linoleic, P is palmitic and S is stearic (Haryati *et al.*, 1998). The concentration of oleic and linoleic acids at low melting temperatures and palmitic and stearic at high temperatures is obvious. The unsaturated and saturated acids may be partially separated first by directed transesterification (Haryati *et al.*, 1998).

The simplest method of fractionation is 'winterisation', which involves cooling the oil slowly, allowing the stearin crystals to settle, and skimming off the liquid fraction, or separating the solid and liquid fractions by centrifugation. Other methods use a solvent or a detergent to achieve a more complete separation of high and low melting fractions. A recent review of fractionation methods was given by Kellens (1996), who stated that the principal method now in use is dry fractionation (no detergent or solvent), with semi-continuous crystallisation, and separation of the fractions by a vacuum filter or a membrane filter press. In the dry method, palm oil is heated and stirred at 70°C for 30 min, then cooled at a carefully controlled rate to around 20°C. The separation of the cooled slurry of crystals is now often done with a membrane filter instead of the conventional suction filter, as this extracts more olein because the filter cake is put under pressure.

14.3.3.2 Hydrogenation

Liquid oils can be hardened by reaction with hydrogen in the presence of a catalyst, the double bonds in unsaturated fatty acids being converted to saturated, single bonds (see Section 13.1.1). Thus, oleic and linoleic acids are converted to stearic acid, with a much higher melting point. After partial hydrogenation, some unsaturated fatty acids will have been converted to saturated, but others will be only partially saturated, and some *trans*-acids will also be formed. These are not found naturally in vegetable oils; they are unsaturated acids which have the same physical shape as saturated acids, unlike the *cis* conformation, which has a bend in the molecule (see Fig. 13.1). It appears that *trans*-acids in the diet have physiological effects similar to, or more harmful than, saturated fatty acids (Section 14.4.1).

The subject of hydrogenation was reviewed by Hastert (1996). The completeness of hydrogenation can be adjusted, depending on the solid fat content required, by varying the reaction conditions: temperature, pressure and type of catalyst. The proportion of *trans*-acids formed also varies with reaction conditions.

14.3.3.3 *Interesterification and transesterification*

Interesterification involves a reaction between triglycerides and fatty acids, alcohols or other esters to produce new esters. Rearrangement within the same molecule constitutes transesterification; heating the oil in the presence of a catalyst results in the random redistribution of fatty acids between triglycerides (see Section 13.1.1). Reaction with methanol produces fatty acid methyl esters (Section 14.3.6.1).

Random transesterification of palm oil causes an increase of about 20% in the solid fat content at 20°C and 30°C (de Graaf, 1976), and is thus an alternative to hydrogenation for some purposes. Interesterification with solid fats may also be used. Interesterification can be directed to the production of specific triglycerides, rather than random, by using lipase enzymes. Xu (2000) reviewed lipase-catalysed production of cocoa butter substitutes, human milk-fat substitutes and other triglycerides with specific structures.

14.3.4 Use of palm oil for edible purposes

In discussing the uses of palm oil below, we use 'palm oil' as a convenient shorthand for both the oil and its fractions and processed products.

Some 90% of the world's palm oil is used for edible purposes (Sambanthamurthi *et al.*, 2000b). Palm oil is a particularly good source of solid fat for many purposes. A good summary of the uses of palm oil in foods was published by the Malaysian Palm Oil Promotion Council (Berger, 1996a). Berger (1996b) gave a review covering much of the same ground, but with references to source literature.

Palm oil and its fractions are used as a cooking oil, in margarines and bakery fats (shortenings), in vanaspati, in confectionery fats (cocoa butter replacers), in ice-creams, and as a replacement for butter fat in some dairy products (coffee whiteners, reconstituted milk, whipped 'cream'). A range of products with high palm oil content has been developed by the Malaysian Palm Oil Board (MPOB). Berger (1990, 1996a) quoted formulations for bakery shortenings containing between 50 and 100% palm oil, margarines with 60–80% palm oil, and vanaspati with 70–80% palm oil. Palm oil may be the only fat in some chocolate-flavoured confectionery and cake coatings, but 100% palm fats are not suitable for ice-cream coatings, as they are too brittle at low temperature.

Palm oil is particularly suitable for deep frying, because it is relatively stable at high temperature, compared with the more unsaturated oils (Berger, 1996a). The polyunsaturated fatty acids, linoleic and linolenic acid, tend to oxidise and break down or polymerise at frying temperatures (180°C), but palm oil contains a relatively small amount of linoleic, and no linolenic acid. Refined red palm oil has been used for deep frying of potato crisps, where it gives a desirable colour to the product (K.G. Berger, pers. comm., 2001).

The use of palm oil midfraction for cocoa butter replacers has already been mentioned. This market is important, because cocoa butter prices are far above those for palm oil, and hence substitutes can command premium prices compared with palm oil. Wong (1993) explained that there are essentially three classes of cocoa butter replacers, which differ in their crystallisation properties, and hence in the extent to which they can be mixed with cocoa butter.

- *Cocoa butter substitutes*: These are incompatible with cocoa butter (Maarsen, 1985) and are used as an alternative for chocolate coatings. They are manufactured mainly from lauric oils or lauric stearins, particularly palm kernel stearin.
- *Cocoa butter extenders*: These can be mixed with cocoa butter to a limited extent. They can be manufactured from palm midfraction or hydrogenated palm olein.
- *Cocoa butter equivalents*: These can be mixed with cocoa butter in any proportions. They can be made from palm midfraction, with the addition of illipe or shea butter.

Berger *et al.* (1978) showed that the stearin fraction from *Elaeis oleifera* oil (erroneously described as hybrid oil in the paper: K.G. Berger, pers. comm., 1979) contained a higher proportion of SUS (saturated–unsaturated–saturated) triglycerides than palm oil or its olein or stearin fractions. Such oil might therefore be a good raw material for production of cocoa butter replacer, if the oil yield of *E. oleifera* or hybrids could be raised to acceptable levels (see Section 5.5.1.6).

Margarines are blends of several different fats to give the required structure. The hard component should have a solid fat content above 80% at 10°C, and at least 15% at 30°C (van Duijn, 2000). Until recently, partial hydrogenation of liquid oils was widely used to produce these components, but with increasing concern over the harmful effects of *trans*-fatty acids in the diet (see Section 14.4.1), a demand for 'trans-free' margarine has developed. This may represent a significant market for palm oil: as Berger (1996a) noted,

trans-free products can be produced using palm and palm kernel oils as sources of solid fat, interesterified with liquid oils. Timms (1990) explained that palm oil crystallises slowly, so that margarines with a high palm oil content are at first too soft, but become too hard in storage. Hydrogenation, interesterification or blending with a faster crystallising lauric oil (coconut or palm kernel) allows the palm oil content of the margarine to be increased. Zainal and Yusoff (1999) described the production of *trans*-free margarine fats by enzyme-catalysed interesterification of palm stearin and palm kernel olein, two products for which there are few other uses. The production of *trans*-free margarines was reviewed by van Duijn (2000). An interesting point in this paper was the comment that over 600 new *trans*-free margarine blends had been developed by Unilever over the previous decade. This gives an indication of the scale of end-use research by the major food companies.

Another product of increasing interest is *trans*-free vanaspati. Aini *et al.* (1999) described the production of this from blends of palm oil and kernel oil fractions.

14.3.5 Palm kernel oil

The lauric oils, palm kernel oil (PKO) and coconut oil, are the main sources of short-chain fatty acids in world trade. PKO contains 44–50% lauric acid (C12) and 15% myristic acid (C14). Both oils have many uses in the edible field; they have a narrow melting range, just below body temperature, which, as noted above for cocoa butter, gives a ‘fresh’ taste to products containing them. For many purposes, they are interchangeable, but PKO has higher oleic and linoleic acid content than coconut oil, and gives a slightly softer fat, with a broader melting range (Maarsen, 1985).

PKO is used for simulated dairy products, such as coffee whiteners. Hydrogenated PKO and palm kernel stearin are used in whipped toppings, and in toffee and caramel. A variety of different PKO derivatives is used in chocolate-flavoured coatings.

14.3.6 Non-food uses of palm oil and kernel oil

14.3.6.1 Oleochemicals

Only about 10% of palm oil is used for non-food products (Sambanthamurthi *et al.*, 2000b). Miyawaki (1998) gave a good summary of where the oleochemicals industry stood at that time. Oleochemicals in general consist of a long carbon chain, one end of which is lipophobic and water soluble, and the other hydrocar-

bon end lipophilic and fat soluble. Such compounds can act as an interface between water and fat, solubilising the latter by dispersing it in small ‘micelles’ throughout the body of the water phase. This surfactant effect is widely used in many domestic and industrial processes. Surfactants are also made from petroleum, but vegetable fats are ideal, being renewable resources, with carbon chains that are easily biodegradable when they enter the natural environment. Hirsinger *et al.* (1995) described a ‘life cycle analysis’ of the production of oleochemicals from palm oil and PKO. This compared the resource use and environmental effects of the entire production chain for oleochemicals, from field to consumer, with that for petrochemical materials (Franke *et al.*, 1995), and showed that palm-derived oleochemicals require less energy for production, and result in lower levels of solid waste and emissions. Wood and Corley (1993) estimated that the energy output of a plantation was over nine times the input.

The production of oleochemicals is essentially the changing of the carboxyl (COOH) group at one end of a fatty acid chain into salts, alcohols, amines, amides, fatty esters or other types of compound (Fig. 14.2).

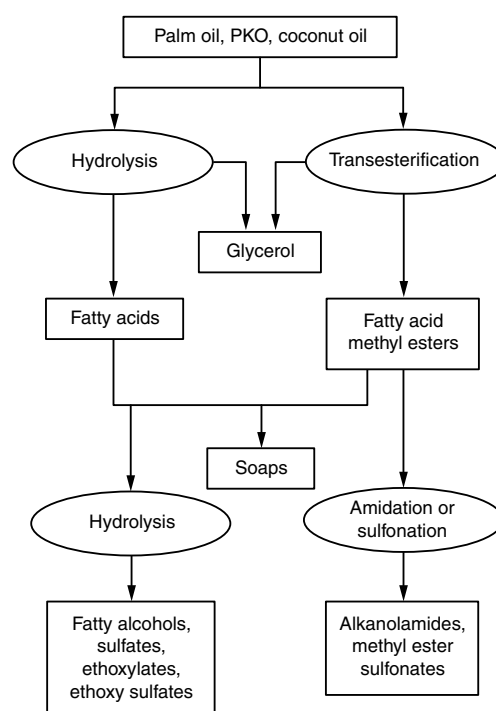


Fig. 14.2 Manufacture of oleochemicals. (Based on Miyawaki, 1998.)

The raw materials are fatty acids, produced by high-temperature splitting of the fat molecule, or the methyl esters of the fatty acids produced by transesterification. Palm oil, PKO, tallow and coconut oil are the main sources. Glycerol is always produced as the fat molecule splits, and is also regarded as an oleochemical, with numerous uses in cosmetics and medicine. Some 6 million tonnes of fat-derived oleochemicals are produced per year, with the Asian industry producing 40% of the world total (Miyawaki, 1998; Salmiah *et al.*, 2000a). Important products include sodium salts (soaps) (Kuntom and Hamirin, 2000) and surfactant derivatives such as methyl ester sulfonates. Palm oil and PKO-derived oleochemicals can be used in lubricants (Margeson and Schwartz, 1993), skin-care products and cosmetics, and have been used experimentally in the drilling industry (Salmiah *et al.*, 2000b). Non-edible uses of lauric oils were listed by Schwitzer (1985).

14.3.6.2 Fuel

Vegetable oils, including palm oil, have been used as fuel in diesel engines for many years; palm oil has particularly been used in producing countries where transport costs or foreign exchange problems have limited petroleum imports. CPO can be used, but the high viscosity causes problems. Baryeh (1990) achieved good results with a 50:50 mixture of PKO and petrol as diesel fuel. Ong *et al.* (1990) described the development of a pilot plant to produce fatty acid methyl esters from palm oil, and the evaluation of these esters for use as diesel fuel (see Choo and Cheah, 2000, for more detail). The fuel was satisfactory, with lower emissions than from standard petroleum-derived fuel.

The economics of using palm oil methyl esters for fuel depended not only on the relative prices of palm oil and diesel oil, but also on the cost of methanol, and the price obtained for glycerol as a by-product. At prices for methanol and glycerol current in 1990, the project appeared viable provided that the palm oil price was no more than 25% above the diesel price (both per tonne, ex-duty) (Ong *et al.*, 1990). Fuel can also be produced in the form of alcohol, by fermentation of carbohydrates, and that could be a competitor for vegetable oil-based fuels.

14.4 PALM OIL AND HUMAN HEALTH

Oils and fats are an essential part of our diet, but the benefits gained may depend in part on the composition of the oil. The controversy over 'tropical oils' in the

human diet is mentioned briefly in Section 1.6.4; the history of the controversy was reviewed by Enig (1998). In this section, we have attempted to sort out some facts from the large volume of propaganda, advertising and partisan comment. Useful reviews are by Cottrell (1991) and Sambanthamurthi *et al.* (2000b).

14.4.1 Oils and fats in human nutrition

Recommendations by the WHO and other bodies are that annual consumption of oils and fats should be at least 12 kg per head, but that oils and fats should not exceed 30% of the daily calorie intake. In much of the developing world, including China and India, the recommended minimum intake level is not reached. Conversely, in Europe and North America, up to 40% of calorie intake may be as oils and fats.

Numerous studies have shown an association between diet and the incidence of coronary heart disease. High fat intake appeared to increase the risk of heart disease and saturated fats appeared to be more harmful than unsaturated. A high blood cholesterol level was also associated with an increased risk of heart disease. In fact, cholesterol is found in the blood in two main forms, in complexes with either high-density lipoprotein (HDL-C) or low-density lipoprotein (LDL-C). It is high levels of the latter form that are associated with heart disease risk, with HDL-C being neutral or perhaps beneficial (Cottrell, 1991). Thus, measurements of LDL-C levels, or of the LDL-C:HDL-C ratio, are likely to be more useful than total cholesterol.

Cottrell (1991), in a keynote paper at a PORIM conference, made a number of important points regarding dietary fats, blood lipids and heart disease. These are summarised below, together with more recent information where available.

1. Cholesterol plays an essential role in the transport and metabolism of fats. The level in the blood depends on a balance between synthesis in the body and uptake from the diet, so that for most people dietary cholesterol has little influence on blood cholesterol level. Vegetable oils themselves contain negligible amounts of cholesterol, but the effects of fatty acids may depend on the dietary cholesterol intake from other sources (see 2, below).
2. An increase in saturated fatty acids in the diet tends to increase blood cholesterol. This relationship is described by the Keys equation, but the work of Keys *et al.* (1957) was based on diets that did not include palm oil. Subsequent work has shown that myristic acid (C14) is more harmful than palmitic or

- stearic acid. Stearic appears to be neutral, while palmitic is only harmful if the level of linoleic acid in the diet is very low. Palmitic acid may also have undesirable effects if the diet is high in cholesterol, but not if it is low (Hayes and Khosla, 1992).
3. A diet high in polyunsaturated fats results in lower total cholesterol, but HDL-C is reduced, as well as LDL-C. In animal studies polyunsaturated fats have been associated with increased risk of cancer, but this does not appear to have been confirmed in human studies.
 4. As noted earlier, if margarine is made from polyunsaturated oils the oil must be hardened. If this is done by partial hydrogenation, then *trans*-fatty acids will be formed. Cottrell quoted a British Nutrition Foundation study which concluded that, at the UK level of less than 6% of dietary fat intake, *trans*-acids would not affect heart disease risk. However, several recent studies have shown that *trans*-acids tend to increase total cholesterol, and to reduce HDL-C and increase LDL-C levels (reviewed by Sambanthamurthi *et al.*, 2000b, and Enig, 1998).
 5. In early work, monounsaturated fatty acids were regarded as neutral, but recent studies indicate that oleic acid is at least as effective as polyunsaturates in lowering total cholesterol and improving the LDL-C:HDL-C ratio (Sambanthamurthi *et al.*, 2000b).

The above points present a simplified picture: the lipoproteins are not the only components of the blood affected by the fats in the diet, and there are many interactions among different dietary components. However, it is clear that no group of natural fatty acids is 'better' than another, and the American Heart Foundation recommends that the fat component of the diet should consist of equal proportions of saturated, monounsaturated and polyunsaturated fatty acids. The view that *trans*-acids should be avoided is gaining strength (see Enig, 1998).

14.4.2 Effects of palm oil in the diet

When the American Soybean Association campaign against 'tropical oils' started in the 1980s, there was actually very little information about the effects of palm oil in the diet. It was assumed that, because the oil contained 50% saturated fatty acids, it would behave like other saturated fats which had been used in trials. Since then, numerous feeding trials with palm oil have been done, many of them sponsored by MPOB, on animals and also with human subjects. These trials were reviewed by Sambanthamurthi *et al.* (2000b).

The majority of studies showed that, in broad terms, a diet with a high proportion of palm oil as the fat component is as healthy as any other. This might be anticipated from the points outlined above. Although palm oil contains 50% saturated fatty acids, these are predominantly palmitic and stearic; the harmful shorter chain saturated fatty acids represent no more than 1.5% of the total. Of the 50% unsaturated fatty acids, most is monounsaturated oleic acid.

There is some evidence that palm oil may inhibit the formation and reduce the growth rate of tumours, but these effects appear to be independent of its fatty acid composition, and may be attributable to some of the minor components in the oil.

14.4.3 Minor constituents of palm oil

Palm oil includes a variety of minor components (carotenoids, tocopherols, chlorophyll, sterols, phosphatides and alcohols), all at concentrations of less than 1000 ppm (see Section 13.1.4.2). Nutritionally, the most important of these are α - and β -carotene, which are precursors of vitamin A, and tocopherols and tocotrienols (vitamin E). Of the carotenes, β -carotene has the strongest provitamin A activity; the importance of carotenoids in human health was recently reviewed by Nicol and Maudet (2000). Vitamin A deficiency can lead to blindness, and the use of red palm oil is a good prophylactic of the condition. There is evidence that tocotrienols have protective effects against heart disease and cancer (reviewed by Sambanthamurthi *et al.*, 2000b).

In conventional refining and fractionation, the carotenes, which give the oil its colour, are destroyed, and about 30% of the tocopherols are also lost (Gapor Mohd Top, 1990). Carotenes are also destroyed during hydrogenation. In view of the nutritional value of these components, methods of extracting them from palm oil have been developed. Ong *et al.* (1990) described the extraction of vitamin E from palm fatty acid distillate (the FFA removed in physical refining), which contains 0.4–0.8% of tocopherols and tocotrienols. Methods of concentrating or extracting carotenes have been described by Ooi *et al.* (1994), Lenfant and Thyron (1996) and Baharin *et al.* (1998).

14.5 CONCLUSIONS

Supplies of palm oil are likely to continue increasing, with large areas in Indonesia that have not yet reached maturity at the time of writing. Palm oil is expected to overtake soya bean oil as the world's leading vegetable

oil before 2005. Production costs should remain below those of other vegetable oils for many years, even if oil palm workers' wages increase significantly in real terms, but in the long term, the cost of harvesting will become a serious problem for the industry. With

increasing supply, the range of uses for palm oil in the oleochemicals industry seems set to continue its steady expansion of recent years. For edible uses, the strengthening opinion against *trans*-acids will favour palm oil as the solid-fat component of product formulations.

Chapter 15

Concluding Remarks

15.1 RESEARCH NEEDS

At fairly frequent intervals the oil palm literature contains papers that set out to review the current research effort, in Malaysia or the world, and from this to suggest what should be done in the future. Two strands of thinking can be detected in these papers. The first sees the future in terms of advanced discoveries, so that the oil palm industry is taking part in agricultural research at the cutting edge (Jalani *et al.*, 1998). The second pays more attention to the immediate needs of the industry, and considers how to deal with existing and pressing problems (Chew *et al.*, 1998). Others (e.g. Tinker, 2000a) accept the need for both types of research, and urge that there should be a reasonable balance between them. Both strands agree in supporting classical or marker-assisted plant breeding, the development of clonal palms, and more research on environmental issues. However, the first strand then focuses on genetic transformation and high biology, and new and exciting uses for oil palm products, as important new developments. The second strand is interested in improving the oil extraction rate, raising the mean field yield and increasing the efficiency of the use of fertiliser and other inputs, especially labour, so as to improve the situation that we already have.

Both approaches are necessary. However, the first strand supports strategic research, and in tree crops the duration of any strategic research programme is likely to be very long. Breeding or transformation programmes can take decades. Even a breeding programme for an annual crop can take 10 years, and it may well take more than 20 years to introduce a major new feature into oil palms, and then to produce a competitive and high-yielding new palm cultivar with this feature. It is essential that this strategic research be undertaken, because the truly long-term prosperity of the industry will depend upon such work. If it is not done, the industry will gradually decline and die. However, the second approach is more immediately useful to a plantation industry trying to remain competitive in a price-sensitive world. Farmers sometimes comment that a long-term strategic research programme is all very well, but will be of little use to

them if they go bankrupt before the project is completed. They may also say that if all farmers have the same improvement from the strategic research, then their own comparative advantage remains unchanged, and only the consumer benefits. This second point is only partly true if there are competing products without the advantage produced by the research, such as the other oil crops.

In this position the overall objective must be to ensure that the oil palm industry in general at least maintains its comparative advantage against other oil crops over both long and short timescales, with both strategic and applied research. For countries and companies, the second objective is that they at least maintain their own relative position within the oil palm industry. Much depends upon the potential for improvement in the shorter term through applied research. For example, the mean annual yield in Malaysia is only one-third of the potential yields of the best modern material, so there does appear to be scope to improve yields, and therefore costs, quite sharply over the short to medium term. In this type of research the application usually demands high standards of management, so that different estates may obtain very different benefits from it.

There is no alternative to a total research programme that covers all these issues, and delivers advances over a broad front. The balance and the management of such a programme require great skill, and its outputs cannot be guaranteed. Many unexpected issues can arise during the course of the long-term programmes, as is discussed below.

15.2 GENETIC MODIFICATION

Genetically modified crops are now widely distributed and successful. However, the developed world is polarised in its view of genetic modification of food crops. Broadly, the US and Japan see few problems, and consider the technology to be entirely safe. In Europe there is a very strong Green movement, based partly on organic farming, that considers genetically modified organisms (GMOs) to be potentially harmful and quite

unacceptable as food crops. The concerns of this movement are that food from GM crops may not be safe because we do not understand the biological consequences of the technique, and that far more testing is required before GMOs are declared to be safe. Activists now look very carefully at every single ingredient in complex food products to make sure that no GMO material is included. This attitude is almost certainly a consequence of the agricultural and food scandals that have affected Europe in recent decades. The second concern is that one cannot predict the consequences of releasing GM crop plants into the environment, and allowing the spread of GM genes through pollen flow. At its simplest, this fear is based upon the idea that 'superweeds' may be developed that cannot be eradicated. Some of the activists involved may never accept GMOs, despite the most authoritative statements about their safety and environmental harmlessness, but the views of the general population are less clear, and may gradually change.

Europe is a major market for palm oil, and at present GM oil would meet a great deal of resistance. Many organisations and supermarket chains now guarantee to their customers that the products they sell do not contain GM materials of any kind. At some point this may change, but the time of this is quite unknown. Possibly the change will occur before GM palm oil can be produced, but this situation must always be kept under observation. The palm oil industry has already had experience of the damage that can be caused by quasi-scientific criticism, in relation to the effects of palm oil on human health.

15.3 THE ENVIRONMENT AND SUSTAINABILITY

15.3.1 General

Rather than bringing everything to do with the environment into a single chapter, we have dealt with environmental matters in the appropriate chapters in this book (Sections 1.4, 3.3, 3.4, 8.1, 8.2, 8.3, 11.1, 11.6, 11.7, 13.4.8). It is however desirable to consider the total impact of the oil palm industry on the environment, and draw a conclusion about its sustainability. The potential complaints against the industry are:

1. Oil palm plantations require the clearing of valuable forest, and therefore damage biodiversity and increase the carbon dioxide content of the atmosphere.
2. Oil palm mills produce large quantities of pollutants that may be disposed of in rivers.

3. Oil palm plantations themselves are monocultures, and use fertilisers and pesticides, and thus attract all the 'green' criticisms directed at modern intensive agriculture (Tinker, 1997).
4. Palm oil as a food is unhealthy (see Section 14.4).

Our conclusions on these points are set out below.

15.3.2 Loss of forest

All agriculture has required the clearing of natural forest or grassland, and most developed countries converted large fractions of their forested area to agriculture long ago. Some land has to be cleared for plantations, but the loss of forest is minimised with oil palm, compared to other crops, because of the high yield of oil per hectare, and because palms can be replanted indefinitely on the same soil, as far as is known. Brazil alone has a larger area of soya beans than the total world area of oil palms (Fearnside, 2001), and this relatively low-yielding crop is starting to encroach into rainforest areas. Almost all temperate arable oil crops have relatively low yields per hectare, even when they are grown under intensive conditions, and have to be subsidised by Governments to overcome this inherent disadvantage in the market. Much present oil palm land was originally cleared for other crops (rubber, cocoa, coconuts in South-east Asia, grassland in Latin America) and has simply been converted to oil palms as a more profitable or less troublesome crop.

The indiscriminate and wasteful approach of some organisations to opening up land in Indonesia for oil palm cultivation (Section 1.4.3.1) is very unfortunate (Casson, 2000), and has given the critics of the industry plenty of ammunition. However, the size of the oil palm industry needs to be put into perspective against the claimed rate of forest loss. FAO (2001) states that the loss of tropical forest is now approximately 13.5 M ha/yr, with 1 M ha/yr regrowth of secondary forest. If the loss continues over 20 years, it will amount to 250 M ha. Mielke (2001) postulated that the oil palm demand would be double the present amount, or an extra 10 M t oil per year, by 2020. The present global area under oil palm is about 6.5 M ha. If we assume that average yields remain the same, the oil palm industry needs an additional 6.5 M ha, or 0.33 M ha per year. Whether this expansion actually happens or not, it only amounts to a little over 2.6% of the expected forest loss. If the yield level is increased by 1% per year, the area needed in 2020 will be roughly 20% less, or about 2.1% of the forest loss.

An associated issue is that of carbon sequestration. Global climate change is largely caused by an increase

in atmospheric carbon dioxide (IPCC, 2001). Any long-term process that removes carbon dioxide, such as an increase in plant biomass or soil carbon, delays this process, and net sequestration can be used for 'carbon trading'. The value of storing a tonne of carbon appears to be roughly US\$10 at present. Tinker (2000a) considered that there was only limited scope for carbon sequestration in oil palm plantations, as forest will normally contain far more carbon than a plantation, and most of the carbon fixed by oil palms returns to carbon dioxide over a few years. However Chan (2002) took a rather more optimistic view of the possibilities.

15.3.3 Pollution

Pollution of soil and rivers results in loss of aquatic biodiversity, and causes other problems by the creation of eutrophic conditions after the release of plant nutrients. However, the pollution from palm oil mills has been virtually completely stopped in Malaysia, and there is very little damage now (see Section 13.4.8). The techniques that have been developed have also included the recycling on to the plantation of a large part of the plant nutrients in the effluents and wastes. This has greatly increased the sustainability of the industry (Section 11.7) and we expect to see the usage of fertiliser decline steadily. These technical solutions to the problem in rivers have been so successful that there is no reason why pollution should be accepted anywhere. Other countries have followed the Malaysian lead in establishing strict regulations to control such pollution, and it seems certain that this issue will diminish rapidly throughout the industry.

15.3.4 Sustainability

A strong argument can be advanced that oil palms are naturally a sustainable crop. In fact, the main environmental question after a forest has been cleared is whether the soil will be irreversibly damaged by its subsequent use. This can happen most easily with arable crops, that encourage erosion. With oil palms the soil is protected to a considerable extent, erosion can be controlled by field techniques, and the soil chemical composition will then normally move gradually to an

acceptable equilibrium steady state. The use of pesticides is far smaller than on most tropical crops, such as cotton or cocoa, and Integrated Pest Management is extensively used (Section 12.2.1). The rate of fertiliser application is indeed large, but in theory the nutrient off-take should be very small because of the low content of nutrient elements in palm oil and kernels (Section 11.7; Vis *et al.*, 2001). The recycling of nutrients is steadily improving.

Cropping produces large yields of a high-energy product per hectare, is repeatable on the same fields, and is not prone to produce erosion. It therefore produces very little damage to natural resources or non-replaceable resources. Palm oil can easily be converted to a substitute for diesel fuel, and this may become a major advantage at some time in the future.

The question of the nutritional value of palm oil is discussed in Section 14.4. It is clear from a great deal of research that palm oil is an entirely satisfactory source of dietary fat, and it is to be hoped that this issue will soon be laid to rest.

15.3.5 Biodiversity

The remaining problem is to manage plantations so as to ensure that biodiversity is better protected. The biodiversity within an oil palm plantation will certainly be less than under natural forest (Andersen, 1996). The diversity of plants is obviously less, and this must lead to a lower diversity of the fauna that lives on and under trees. More research on this issue is needed. Sustainability demands that marginal land with steep slopes or unsuitable soil, on which soil damage is likely, should not be used for plantations. The ideal situation is to leave forest 'islands' within plantations as habitat for a more diverse biota, and these islands can be the parts of the estate less suitable for oil palms. The industry needs to accept that a mixed landscape with such islands must be managed to contribute to biodiversity conservation. The situation to aim for is a matrix of oil palm areas and natural forest, as a system of landscape conservation. Much more needs to be known about landscape ecology, so that landscapes can be designed to include both efficient plantations and conservation areas for wildlife (Szaro and Johnson 1996).

Reference list and index of citations

Sections in which papers are cited are indicated in square brackets. References to tables and figures are numbered according to the section in which they appear.

- AAR (1999) *AAR Research News*, Oct. 1999, Applied Agricultural Research, Sungei Buloh, Malaysia [11.3.1; 11.6.1.4; 11.6.2.4]
- Abdul Majid R. (1999) Adopting the zero-burning technique in new clearings – Mentiga's experience. *Planter, Kuala Lumpur*, 75, 391–401 [8.3.2]
- Abigor D.R., Opute F.I., Opoku A.R. & Osagie A.U. (1985) Partial purification and some properties of the lipase present in oil palm (*Elaeis guineensis*) mesocarp. *J. Sci. Food Agric.*, 36, 599–606 [13.3.3]
- Abramsky Z., Strauss E., Subach A., Kotler B.P. & Riechman A. (1996) The effect of barn owls (*Tyto alba*) on the activity and microhabitat selection of *Gerbillus allenbyi* and *G. pyramidum*. *Oecologia*, 105, 313–319 [12.3.1]
- Abu Hassan O. & Yeong S.W. (1999) By-products as animal feed-stuffs. In: *Oil palm and the environment – a Malaysian perspective*, (Ed. by Gurmit Singh *et al.*), pp. 225–239, Malay. Oil Palm Growers' Council, Kuala Lumpur [11.7.3]
- Acevedo J.A., Buritica P., Garcia J.A. & Galvis N. (2000) Valoración económica de las pérdidas en aceite generadas por la pudrición de cogollo en los Llanos Orientales de Colombia. *Palmas (Bogota)*, 21 (2), 53–62 [12.1.7.2]
- Acosta A., Munevar F., Gomez P.L. & Santacruz L. (2002) Nutritional factors associated with bud rot disease in oil palm plantations in Colombia. Paper presented at 2002 Int. Oil palm Conf. Bali, 8–12 July, Indonesian Oil Palm Res. Inst. [12.1.7.2]
- Acres B., Bower R.B., Burroughs C.J., Folland M.S., Kalsi M.S., Thomas P. & Wright P.S. (1975) *The soils of Sabah*, Vols 1–5, Land Resources Division, Ministry of Overseas Development, UK [3.4.1.3]
- Aderungboye F.O. (1982) Significance of vascular wilt in oil palm plantations in Nigeria. In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 475–484, Incomp. Soc. Planters, Kuala Lumpur [12.1.6.2]
- Adidharma D. (2002) *Biological control of rats (Rattus tiomanicus Miller) using barn owls (Tyto alba) at PT Astra Agro Lestari Tbk*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [12.3.1]
- Adiwiganda R. (2002) *Defining the nutrient formulation and its minimum dosage of compound fertilisers based on the nutrient status of soil subgroup in oil palm plantation of Indonesia*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July [11.9.2.6]
- Adiwiganda R., Koedadiri A.D. & Poeloengan Z. (1993) Characterisation of a spodosol of the Minas geological formation. *Bull. Pusat Penelitian Kelapa Savit*, 1, 163–173 [3.4.3.6; 8.1.3.3]
- Adiwiganda R., Siregar H.H. & Sutarta E.S. (1999) Agroclimatic zones for oil palm (*Elaeis guineensis* Jacq.) plantation in Indonesia. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 387–401, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.3.1; 8.1.5.3]
- Adje I.A. & Adjadi E. (2001) Diffusion du matériel végétal amélioré palmier à huile en milieu villageois: l'expérience du Benin. *Ol Corps Gras Lipides*, 8, 529–533 [1.5.3]
- Agamuthu P. & Broughton W.J. (1985) Nutrient cycling within the developing oil palm–legume ecosystem. *Agric. Ecosyst. Environ.*, 13, 111–123 [8.4.2; 10.1.2.4]
- Agamuthu P. & Broughton W.J. (1986) Factors affecting the development of the rooting system in young oil palms (*Elaeis guineensis* Jacq.). *Agric. Ecosystems & Environ.*, 17, 173–179 [11.2.1.2]
- Agamuthu P. & Ho C.C. (1992) Quantification of endogenous cytokinins in the flower primordia of normal seed-derived and mantled tissue-culture derived oil palm. *Trans. Malay. Soc. Pl. Physiol.*, 3, 143–150 [6.3.1.2]
- Agamuthu P., Krause A., Broughton W.J. & Ho C.C. (1996) The possible role of homeotic genes in flower morphogenesis in oil palm (*Elaeis guineensis* Jacq.). *Asia-Pacific J. Molec. Biol. Biotech.*, 4, 103–105 [6.3.1.2]
- Ahiekpor E.S.S. & Yap T.C. (1982) Heritability, correlation and path coefficient analyses of some oil palm breeding populations in Malaysia. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 47–54, Incomp. Soc. Planters, Kuala Lumpur [5.3.2; 5.3.3.2]
- Ahmad Alwi & Chan K.W. (1990) The future of oil palm yield forecasting: Guthrie's autoregressive integrated moving average method. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 144–150, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.5.4]
- Ahmad Hitam & Ahmad Zamri M.Y. (1996) Tracked vehicle for fruit infield collection. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 277–279, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.2; 10.4.4.2; 10.4.7]
- Ahmad Hitam & Ahmad Zamri M.Y. (2000) Mechanisation in oil palm plantations. In: *Advances in oil palm research*, Vol. I (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 653–696, Malaysian Palm Oil Board, Kuala Lumpur [10.4.5; 10.4.6; 10.4.7]
- Ahmad Sarwani A., Chang A.K., Ho C.T., Teoh C.H. & Padzil Ariffin M. (1999) Environmental Impact assessment in oil palm planting from secondary forest – Golden Hope's experiences. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 183–197, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.1.7; 10.7.2]
- Aini I.N., Maimon C.H.C., Hanirah H., Zawiah S. & Man Y.B.C. (1999) Trans-free vanaspati containing ternary blends of palm

- oil-palm stearin-palm olein and palm oil-palm stearin-palm kernel olein. *J. Amer. Oil Chem. Soc.*, **76**, 643–648 [14.3.4]
- Airede C.E., Appiah P.O., Osagie I.J. & Kolade K.O. (1999) Prospecting for biocontrol agents in the integrated control of oil palm pests *Coelaenomenodera elaeidis* and *Homophylotis catori* in Nigeria. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 252–263, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2]
- Akbar U., Kusnadi M. & Ollagnier M. (1971) Influence de la nature du matériel végétal et de la nutrition minérale sur la pourriture sèche du tronc du palmier à huile due à *Ganoderma. Oléagineux*, **26**, 527–534 [12.1.6.3]
- Akubuo C.O. & Eje B.E. (2002) Palm kernel and shell separator. *Biosystems Engineering*, **81**, 193–199 [13.4.3.7]
- Alang Z.C. (1982) Some physiological effects of the commercial heat treatment of oil palm (*Elaeis guineensis*) seeds. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 207–222, Incomp. Soc. Planters, Kuala Lumpur [7.1.1.1]
- Alang Z.C., Moir G.F.J. & Jones L.H. (1988) Composition, degradation and utilization of endosperm during germination in the oil palm (*Elaeis guineensis* Jacq.). *Ann. Bot.*, **61**, 261–268 [2.2.1.2]
- Alexander V.T. & Kastelein P. (1983) Hartrot or 'sudden wilt' disease in hybrids of *Elaeis oleifera* × *Elaeis guineensis*. *Surinaamse Landbouw (Suriname)*, **31**, 18–22 [12.1.6.4]
- Alibert R. (1945) Pourquoi et comment on fait la fécondation artificielle sur le palmier à huile. *Farm Forest*, **6**, 27–30 [2.2.2.5]
- Ali Sekak M., Ooi S.C. & Noh H.J. (1981) Chemical induction of inflorescence abortion in oil palm (*Elaeis guineensis* Jacq.). *Malay. agric. Res. Dev. Inst. Res. Bull.*, **8**, 144–154 [4.4.5.1; 4.5.1]
- Alizaga R., Zeledon M.E. & Jimenez R. (1994) Calibration of a capacitance-type moisture meter for oil palm kernels (*Elaeis guineensis*). *ASD Oil Palm Papers*, **8**, 1–6 [7.1.3.1]
- Allen R.G., Smith M., Pereira L.S. & Perrier A. (1994) An update for the calculation of reference evapotranspiration. *ICID Bull.*, **43**, 35–92 [10.3.1.1]
- Allen R.G., Pereira L.S., Raes D. & Smith M. (1998) *Crop evapotranspiration: guidelines for computing crop water requirements*. FAO irrigation and drainage paper No. 56, FAO, Rome [3.2.2.1]
- Alvarado A., Chinchilla C.M., Bulgarelli J. & Sterling F. (1997) Agronomic factors associated to common spear rot/crown disease in oil palm. *ASD Oil Palm Papers*, **15**, 8–28 [12.1.5.1; 12.1.7.2]
- Ambika S.R. (2002) Allelopathic plants. 6. *Chromolaena odorata* (L.) King and Robinson. *Allelopathy J.*, **9**, 35–41 [10.1.2.2]
- Aminuddin & Ching C.L. (1992) *Pamol's experience in oil palm underplanting in Sabah*. Paper presented at Incomp. Soc. Planters Seminar 'Advances in cocoa and oil palm in meeting future challenges', 16–17 June, Lahad Datu, Sabah [8.3.4.3]
- Amir H.G., Shamsuddin Z.H., Halimi M.S., Ramlan M.F. & Marziah M. (2001) Effects of *Azospirillum* inoculation on N₂ fixation and growth of oil palm plantlets at nursery stage. *J. Oil Palm Res.*, **13**, 42–49 [10.1.2.4; 11.2.3]
- Amiruddin M.D. (1993) *In vitro screening of oil palm (Elaeis guineensis Jacq.) clones for resistance towards Ganoderma*. Thesis, Univ. of Reading, Reading [12.1.6.3]
- Amoah F.M., Nuerterty B.N., Baidoado K., Oseibonsu K. & Asamoah T. (1995) Underplanting of oil palm with cocoa in Ghana. *Agroforestry Syst.*, **30**, 289–299 [8.4.3.3]
- Amthor J.S. (2000) The McCree–de Wit–Penning de Vries–Thornley respiration paradigms: 30 years later. *Ann. Bot.*, **86**, 1–20 [4.1.4.3]
- Andah B.W. (1993) Identifying early farming traditions of West Africa. In: *Archaeology of Africa: food, metals and towns*, pp. 240–254, Routledge [1.2.2]
- Anderson J.M. (1996) Functional values of biodiversity in oil palm plantations: concepts and approaches for sustainable production. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 113–128, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.2.1; 15.3.5]
- Andren H. (1994) Effect of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *Oikos*, **71**, 355–366 [8.2.1]
- Andriess J.P. (1988) *Nature and management of tropical soils*. FAO Soils Bulletin 59, FAO, Rome [3.4.3.7]
- Anon. (1956) Notes on the botany of the oil palm. 2. The seedling. *J.W. Afr. Inst. Oil Palm Res.*, **2**, 92–95 [2.2.1.1; 2.2.1.2]
- Anon. (1961) Notes on the botany of the oil palm. 3. The stem and the stem apex. *J.W. Afr. Inst. Oil Palm Res.*, **3**, 277–279 [2.2.1.3]
- Anon. (1962) Notes on the botany of the oil palm. 4. The leaf. *J.W. Afr. Inst. Oil Palm Res.*, **3**, 350–352 [2.2.1.4]
- Anon. (1983) Le plan quinquennal de développement économique de la Côte d'Ivoire. *Afrique Agric.*, **90**, 41–63 [1.4.3.6]
- Anon. (1990) Notes on field trials visited at Bah Lias Research Station. In: *Proc. Workshop 'Progress of oil palm breeding populations'*, pp. 131–148, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.1; 5.1.6.2]
- Anon. (1999) Latin America: key global oilseed area. *Inform*, **10**, 1096–1113 [1.4.3.8; 1.4.3.9]
- Anupunt P., Sarakoon N., Mamewattana S. & Pongmanawut D. (1998) Oil and kernel contents of oil palm bunches of Thailand. In: *Proc. 1996 Int. Conf. 'Oil and kernel production in oil palm – a global perspective'* (Ed. by N. Rajanaidu, I.E. Henson & B.S. Jalani), pp. 330–336, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.2]
- Arasu N.T. (1970a) Foliar spiral and yield in oil palms (*Elaeis guineensis* Jacq.). *Malay. agric. J.*, **47**, 409–415 [2.2.1.3]
- Arasu N.T. (1970b) A note on the germination of *pisifera* (shell-less) oil palm seeds. *Malay. agric. J.*, **47**, 524–527 [7.1.4.5]
- Ariffin D. & Idris A.S. (1993) Investigation on the control of *Ganoderma* with Dazomet. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 424–429, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.3]
- Ariffin D. & Jalani B.S. (Eds) (1994) *Proc. National Seminar 'Palm oil extraction rate: problems and issues'*. Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.5.2; 10.5.2]
- Ariffin D., Gurmit S. & Lim T.K. (1990) *Ganoderma* in Malaysia – current status and research strategy. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 294–297, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.3]
- Ariffin D., Idris A.S. & Khairudin H. (1995a) Confirmation of *Ganoderma* infected palm by drilling technique. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et*

- al.), pp. 735–738, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.3]
- Ariffin D., Seman I.A. & Azahari M. (1995b) *Development of a technique to screen oil palm seedlings for resistance to Ganoderma*. Paper presented at 1995 PORIM Nat. Oil Palm Conf. 'Technologies in plantation – the way forward', 11–12 July, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.3]
- Ariffin D., Idris A.S. & Gurmit S. (2000) Status of *Ganoderma* in oil palm. In: *Ganoderma diseases of perennial crops* (Ed. by J. Flood, P.D. Bridge & M. Holderness), pp. 49–68, CABI Publishing, Wallingford [12.1.6.3]
- Ariff Omar M. (1999) Palm oil and beef – a smart combination of enterprises. *Planter, Kuala Lumpur*, 75, 429–431 [8.4.3.4]
- Arnaud F. & Rabechault H. (1972) Premières observations sur les caractères cytohistochimiques de la résistance du palmier à huile au 'déperissement brutal'. *Oléagineux*, 27, 525–529 [2.3.2]
- Asamoah T.E.O. & Nuertey B.N. (1989) *Preliminary results from an oil palm progeny, density and location trial in Ghana*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [9.3.3.1]
- Asante S.K. & Kumar R. (1986) Biology of *Temnoschoita quadrimaculata* Gly. (Coleoptera: Curculionidae) on oil palm in Ghana. *Insect Sci. Applic.*, 7, 129–134 [12.2.4.3]
- Asmady H., Jacquemard J.C., Hayun Z., Indra S. & Durand-Gasselin T. (2002) *Variety output and oil palm (Elaeis guineensis Jacq.) improvement: the P.T. Socfin Indonesia example*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [5.2.1.2]
- Asmono D., Ikwon M. & Purba A.R. (1999) Genetic improvement of IOPRI oil palm using *pisifera* derived from Congo germplasm. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 351–369, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.3; 5.5.1.2; 5.5.1.4]
- Ataga C.D. (1986) *Some policy considerations for the Nigerian oil palm industry*. Paper presented at Int. Conf Oil Palm, Port Harcourt, Nigeria, 9–16 Nov. [1.4.3.4]
- Ataga C.D. & Fatokun C.A. (1989a) *Multivariate studies of the Nigerian oil palm (Elaeis guineensis Jacq.) germplasm collection*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [5.1.7.1]
- Ataga C.D. & Fatokun C.A. (1989b) Disc polyacrylamide gel electrophoresis of pollen proteins in the oil palm (*Elaeis*). *Euphytica*, 40, 83–83 [5.2.8.1]
- Ataga C.D., Okwuagwu C.O. & Okolo E.C. (1999) Characterisation of a recent oil palm (*Elaeis guineensis*) germplasm collection and its exploitation in Nigeria. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 277–280, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.7.1]
- Atkinson D. & Mackie-Dawson L.A. (2001) Root growth: methods of measurement. In: *Soil analysis: physical methods* (Ed. by K.A. Smith & C.E. Mullins), Marcel Dekker, New York [11.2.1.2]
- Aulakh M.S., Doran J.W. & Mosier A.R. (1992) Soil denitrification – significance, measurement and effects of management. *Adv. Soil Sci.*, 18, 1–58 [11.7.4.2]
- Aya F.O. (1974) The use of polyethylene bags for raising oil palm seedlings in Nigeria. 1. Relative performance of seedlings grown in ground beds and polyethylene bags in the nursery. *J. Nigerian Inst. Oil Palm Res.*, 5 (19), 7–12 [7.2.2]
- Aya F.O. (1979) The use of polyethylene bags for raising oil palm seedlings in Nigeria. 2. The influence of bag size, colour, drainage, and planting date on the performance of the seedlings in the nursery. *J. Nigerian Inst. Oil Palm Res.*, 5 (20), 15–20 [7.2.2.2]
- Ayala A. (1999) Metodología para la selección de progenitores de palma de aciete (*Elaeis guineensis* Jacq.) resistentes a pudrición de cogollo. *Ceniavances*, 63, 1–3 [12.1.7.2]
- Azman H.M.Y., Lee C.H. & Razak I.A. (1998) Oil and kernel yields of oil palm in relation to planting densities, materials and fertiliser rates. In: *Proc. 1996 Int. Conf. 'Oil and kernel production in oil palm – a global perspective'* (Ed. by N. Rajanaidu, I.E. Henson & B.S. Jalani), pp. 109–119, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.7]
- Azmi Yahya & El Pebrian D. (2001) Mechanised field transplanting of oil palm seedling. *Planter, Kuala Lumpur*, 77, 723–745 [9.4.2]
- Bachy A. (1958) Le 'Blast' des pépinières de palmier à huile. *Oléagineux*, 13, 653–660 [7.2.4; 12.1.4]
- Bachy A. (1964) Tropisme racinaire du palmier à huile. *Oléagineux*, 19, 684–685 [2.2.1.5]
- Bachy A. (1965) Influence de l'éclaircie naturelle sur la production du palmier à huile. *Oléagineux*, 20, 575–577 [9.3.6.1]
- Badmus G.A. (1993) NIFOR automated small scale oil palm fruit processing equipment – its need, development and cost effectiveness. In: *Proc. 1991 Int. Oil Palm Conf. – Chemistry & technology* (Ed. by Y. Basiron et al.), pp. 20–31, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.4]
- Baharin B.S., Rahman K.A., Karim M.I.A., Oyaizu T., Tanaka K., Tanaka Y. & Takagi S. (1998) Separation of palm carotene from crude palm oil by adsorption chromatography with a synthetic polymer adsorbent. *J. Amer. Oil Chem. Soc.*, 75, 399–404 [14.4.3]
- Bakoumé C., Adon B., Cochard B., Potier F., Durand Gasselin T. & Amblard P. (2001) Assessment of Yocoboué wild oil palm (*Elaeis guineensis* Jacq.) from Côte d'Ivoire. *Euphytica*, 121, 59–64 [5.1.7.1]
- Ballo K.C. & Quencez P. (1991) Planting on continuous terraces along contour lines – design adapted to agronomy experiments. *Oléagineux*, 46, 515–526 [8.3.5]
- Ballo K., Quencez P., Ouattara S. & Tailliez B. (1995) Border effect in a control plot of a potassium fertiliser trial on exhausted soils in the Ivory Coast. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani et al.), pp. 614–619, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.2.1.3; 11.3.2.1]
- Barber S. (1995) *Soil nutrient bioavailability*. Wiley & Sons, New York [11.1.1; 11.2.1.1; 11.2.1.3; 11.6.1.3; 11.9.3]
- Barcelos E. & Amblard P. (1999) Oil palm breeding programme at EMBRAPA/Brazil. In: *Proc. Seminar 'Science of oil palm breeding' (Montpellier, 1992)* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 190–203, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.3]
- Barcelos E., Miranda Santos M.d., Elizabeth M. & Varoncellos C. (1986) Phenotypic variation in natural populations of Caiaue, *Elaeis oleifera*, H.B.K. Cortes, in the Brazilian Amazon. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 102–116, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.7.3]
- Barcelos E., Second S., Kahn F., Amblard P., Lebrun P. & Seguin M. (1999) Molecular markers applied to the analysis of genetic

- diversity and to the biogeography of *Elaeis* (Palmae). In: *Evolution, variation and classification of palms. Memoirs 83 of the New York Botanical Garden*, (Ed. by A. Henderson & F. Borchsenius), pp. 191–201, New York Botanical Garden Press, New York [2.1]
- Barcelos E., Amblard P., Berthaud J. & Seguin M. (2002) Genetic diversity and relationship in American and African oil palm as revealed by RFLP and AFLP molecular markers. *Pesq. Agropec. Brasil.*, **37**, 1105–1114 [5.1.7.3]
- Barlow H.S. & Chew P.S. (1971) The rhinoceros beetle *Oryctes rhinoceros*, in young oil palms replanted after rubber on some estates in Western Malaysia. In: *Crop protection in Malaysia*, (Ed. by R.L. Wastie & B.J. Wood), pp. 133–144, Incomp. Soc. Planters, Kuala Lumpur [12.2.4.1]
- Barnabe G.A.H. (1976) Field planting of young oil palms raised in polythene bags (polybags). *Oléagineux*, **31**, 260–261 [9.1.1]
- Barrow N.J. (1983) A mechanistic model for describing the sorption and desorption of phosphate by soil. *J. Soil Sci.*, **34**, 733–750 [11.9.2.3]
- Baryeh E.A. (1990) Performance of a diesel engine using palm oil/petrol and palm kernel oil/petrol blends as fuel. *Agric. Int.*, **42**, 246–248 [14.3.6.2]
- Baryeh E.A. (2001) Effects of palm oil processing parameters on yield. *J. Food Eng.*, **48**, 1–6 [13.4.4]
- Basiron Y. (2000) Short-term strategies to sustain oil palm prices. *Planter, Kuala Lumpur*, **76**, 669–670 [1.4.2; 8.3.4.1]
- Basiron Y. & Salmiah A. (1994) Potential new value-added products from palm oil and palm kernel oil. In: *Management for enhanced profitability in plantations* (Ed. by Chee K.H.), pp. 409–418, Incomp. Soc. Planters, Kuala Lumpur [1.6.3.1; 1.6.3.2]
- Basri Wahid M. & Halim Hassan A. (1985) The effects of *Elaeidobius kamerunicus* Faust on rat control programmes of oil palm estates in Malaysia. *Palm Oil Res. Inst. Malaysia, Occ. Paper*, **14**, 1–50 [12.5.1]
- Basri Wahid M., Sharma M. & Kamarudin N. (1991) Field evaluation of insecticides and a cultural practice against the bunch moth, *Tirathaba rufivena* (Lepidoptera: Pyralidae) in a mature oil palm plantation. *Elaeis*, **3**, 355–362 [12.2.8.1]
- Basri Wahid M., Siti Ramlah A.A., Ramle Moslim & Arshad O. (1996) Biological efficacy of three commercial products of *Bacillus thuringiensis* for the control of bagworms, *Metisa plana* and *Mahasena corbetti* (Lepidoptera: Psychidae) of oil palm. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 369–378, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.5.2]
- Bass A. & Hughes W. (1984) Conditions for isolation and regeneration of viable protoplasts of oil palm (*Elaeis guineensis*). *Pl. Cell Rep.*, **3**, 169–171 [6.6.1.2]
- Bastidas S., Figueredo P. & Reyes R. (1993) Obtención de materiales de palma de aceite (*Elaeis guineensis* Jacq.) adaptados al trópico latinoamericano. *Palmas (Bogota)*, **14**, 49–56 [5.1.6.3]
- Bastin G. (1990) The techno-economic strength of palm oil: competitive position in Europe in the 1990s. In: *Proc. Symp. 'New developments in palm oil'* (Ed. by K.G. Berger), pp. 1–8, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.1.1; 14.2.2]
- Baudouin L. (1987) A method for correcting soil heterogeneity to estimate genotypic value for the selection of adult ortet palms in oil palm experiments. In: *Proc. Colloquium Breeding and selection for clonal oil palms* (Ed. by Soh A.C., N. Rajanaidu & M.N. Hasan Basri), pp. 70–76, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.4.1]
- Baudouin L. (1992) Use of molecular markers for oil palm breeding 1. Protein markers. *Oléagineux*, **47**, 681–691 [5.2.8.1]
- Baudouin L. & Durand-Gasselin T. (1991) Genetic transmission of characters linked to oil yields in oil palm by cloning results for young palms. *Oléagineux*, **46**, 313–320 [5.3.2; 5.3.3.2; 6.4.1]
- Baudouin L., Asmady & Noiret J.M. (1987) Importance of environmental factors in the choice of oil palm ortets. *Oléagineux*, **42**, 263–269 [6.4.1]
- Baudouin L., Meunier J. & Noiret J.M. (1995) Methods used for ortet choice. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 217–224, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.4.1]
- Baudouin L., Baril C., Clément-Demange A., Leroy T. & Paulin D. (1997) Recurrent selection of tropical tree crops. *Euphytica*, **96**, 101–114 [5.1.6.1; 5.4.2.1]
- Bealing F.J. & Haniff Harun M. (1989) Inflorescence abortion and sex determination in oil palm. *Palm Oil Res. Inst. Malaysia, Bull.*, **18**, 1–19 [4.2.2.2; 4.4.5.4]
- Beccari O. (1914a) Contributo alle conoscenze della palma a olio. *Agricoltura Colon.*, **8**, 255–270 [2.2.2.6]
- Beccari O. (1914b) *Palme del Madagascar*, Florence [2.1]
- Beckett P.H.T. (1964) Studies on soil potassium. II. The immediate Q/I relation of labile potassium in the soil. *J. Soil Sci.*, **15**, 9–23 [11.6.4]
- Beirnaert A. (1933a) Les bases de la sélection du palmier à huile. *J. Agron. Colon.*, **1933**, 124–134 [5.1.2]
- Beirnaert A. (1933b) Les méthodes de la sélection du palmier à huile. *J. Agron. Colon.*, **1933**, 135–146 [5.1.2]
- Beirnaert A. (1933c) La sélection du palmier à huile. *Bull. agric. Congo Belge*, **24**, 359–380, 418–458 [5.1.2; 5.4.1.2]
- Beirnaert A. (1935a) Introduction à la biologie florale du palmier *Elaeis*. Organisation de l'inflorescence chez le palmier à huile. *Rev. Int. Bot. appl. Agric. Trop.*, **15**, 1091–1108 [2.2.2.1]
- Beirnaert A. (1935b) Introduction à la biologie florale du palmier à huile (*Elaeis guineensis* Jacquin). *Publ. Inst. Nat. Etude agron. Congo Belge, Ser. Sci.*, **5**, 3–42 [2.2.2; 4.2.1.1; 4.4]
- Beirnaert A. (1940) Le problème de la stérilité chez le palmier à huile. *Bull. agric. Congo Belge*, **3**, 95–110 [5.1.5]
- Beirnaert A. & Vanderweylen R. (1941) Contribution à l'étude génétique et biométrique des variétés d'*Elaeis guineensis* Jacquin. *Publ. Inst. Nat. Etude agron. Congo Belge, Ser. Sci.*, **27**, 1–101 [2.2; 5.1.5; 5.2.1.1; 5.3.3.1; 5.3.3.3; 5.3.4.4]
- Bek-Nielsen B. (1969) Quality aspects of oil palm kernel production. In: *The quality and marketing of palm oil products* (Ed. by P.D. Turner), pp. 161–168, Incomp. Soc. Planters, Kuala Lumpur [13.4.3.7]
- Bek-Nielsen C., Bek-Nielsen M., Gurmit S. & Sharma M. (2000) Managing resources resourcefully – a corporate strategy. In: *Managing oil palm for high yields: agronomic principles*, (Ed. by Goh K.J.), pp. 1–27, Malaysian Society of Soil Science and Param Agricultural Surveys, Kuala Lumpur [10.2]
- Bellier L. (1965) Évolution du peuplement des rongeurs dans les plantations industrielles de palmier à huile. *Oléagineux*, **20**, 735–737 [12.3.1]
- Bénard G. & Daniel C. (1971) Economie de l'eau en jeunes palmeraies sélectionnées du Dahomey – castration et sol nu. *Oléagineux*, **26**, 225–232 [4.3.7.3; 10.4.2]
- Bénard G. & Noiret J.M. (1970) Le pollen de palmier à huile.

- Recolte, préparation, conditionnement et utilisation pour la fécondation artificielle. *Oléagineux*, 25, 67–73 [5.2.1.2]
- Bergami Filho A., Amorim L., Laranjeira F.F., Berger R.D. & Hau B. (1998) Análise temporal do amarelecimento fatal do dendezeiro como ferramenta para elucidar sua etiologia. *Fitopatol. bras.*, 23, 391–396 [12.1.7.2]
- Berger K.G. (1981) Food uses of palm oil. *Palm Oil Res. Inst. Malaysia, Occ. Paper*, 2, 1–30 [1.6.4]
- Berger K.G. (1983) Problems in palm oil handling and storage. In: *Proc. Regional Workshop 'Palm oil mill technology and effluent treatment'*, pp. 112–118, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.3.6; 13.4.6.1; 13.4.6.2]
- Berger K.G. (1985) Handling and storage of palm oil. In: *Proc. Workshop Quality in the palm oil industry*, pp. 80–87, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.3.6]
- Berger K.G. (1990) Recent developments in palm oil. *Oléagineux*, 45, 437–447 [14.3.4]
- Berger K.G. (1996a) *Food uses of palm oil*, Malaysian Palm Oil Promotion Council, Kuala Lumpur [13.1.2; 14.3]
- Berger K.G. (1996b) Recent results on palm oil uses in food products. In: *Proc. World Conf. Oil Seed Processing*, pp. 151–155, Istanbul [14.3.4]
- Berger K.G. (2000) *The development of the Codex Alimentarius code of practice for handling edible oils and fats*. Meeting of SCI Oils & Fats Group on Palm Oil Supply Chain, London, 19th Sept. [13.4.3.6]
- Berger K.G., Hamilton R.J. & Tan B.K. (1978) Triglyceride structure of *Elaeis guineensis* var *tenera* and a hybrid of *E. guineensis* × *E. melanococca*. *Chem. Ind.*, 3, 383–384 [13.1.3; 14.3.4]
- Berti N. & Mariau D. (1999) *Coelaenomenodera lameensis* n. sp., ravageur du palmier à huile (Coleoptera, Chrysomelidae). *Nouv. Rev. Ent.*, 16, 253–267 [12.2.5.5]
- Bertossi F.A., Chabrilange N. & Duval Y. (2001) Absciscic acid and desiccation tolerance in oil palm (*Elaeis guineensis* Jacq.) somatic embryos. *Genet. Select. Evol.*, 33, S75–S84 [6.2.3]
- Besse I., Verdeil J.L., Duval Y., Sotta B., Maldiney R. & Miginiac E. (1992) Oil palm (*Elaeis guineensis* Jacq.) clonal fidelity: endogenous cytokinins and indoleacetic acid in embryogenic callus cultures. *J. exp. Bot.*, 43, 983–989 [6.3.1.2; 6.3.3]
- Beuther E., Wiese U., Lukacs N., van Slobbe W.G. & Riesner D. (1992) Fatal yellowing of oil palms – search for viroids and double-stranded RNA. *J. Phytopathol.*, 136, 297–311 [12.1.7.2]
- Bevan J.W.L. & Gray B.S. (1966) Germination and nursery techniques for the oil palm in Malaysia. *Planter, Kuala Lumpur*, 42, 165–187 [7.2]
- Bevan J.W.L. & Gray B.S. (1969) *The organisation and control of field practice for large-scale oil palm plantings in Malaysia*. In: *Incorp. Soc. Planters, Kuala Lumpur* [7.2.2.3; 7.2.5; 9.4.2]
- Bevan J.W.L., Fleming T. & Gray B.S. (1966) *Planting techniques for oil palms in Malaysia*. In: *Incorp. Soc. Planters, Kuala Lumpur* [7.1.3.1; 8.2.2]
- Bilal M., Veerappan P. & Nazeeb M. (1999) Evaluation of Deli-Nigerian D × T and Avros-Nigerian T × T crosses in Sime Darby Plantations. In: *Proc. Seminar 'PS1 and PS2 oil palm planting materials'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 54–64, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.4.1]
- Billotte N., Frances L., Amblard P., Durand-Gasselin T., Noyer J.L. & Courtois B. (2001) Search for AFLP and microsatellite markers of the SH gene in oil palm (*Elaeis guineensis* Jacq.) by bulk segregant analysis (BSA) and by genetic mapping. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, p. 442, Malaysian Palm Oil Board, Kuala Lumpur [5.2.8.1; 5.2.8.3]
- Blaak G. (1965) Breeding and inheritance in the oil palm (*Elaeis guineensis* Jacq.) Part III. Yield selection and inheritance. *J.W. Afr. Inst. Oil Palm Res.*, 4, 262–283 [5.2.3; 5.3.2]
- Blaak G. (1970a) L'extraction de l'huile, a froid, dans l'analyse des régimes de palmier à huile. *Oléagineux*, 25, 165–168 [5.2.4.2]
- Blaak G. (1970b) Epistasis for crown disease in the oil palm (*Elaeis guineensis* Jacq.). *Euphytica*, 19, 22–24 [5.3.5; 12.1.5.1]
- Blaak G. (1972) Prediction of precocity in the oil palm (*Elaeis guineensis* Jacq.). *Euphytica*, 21, 22–26 [5.3.2]
- Blaak G. (1979) A village palm oil mill. *Oil Palm News*, 23, 5–11 [13.4.4]
- Blaak G. (1989) *New concepts in low cost, small scale oil palm bunch processing in West Africa*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [13.4.4]
- Blaak G. & Sterling F. (1996) The prospects of extending oil palm cultivation to higher elevations through using cold-tolerant planting material. *Planter, Kuala Lumpur*, 72, 645–652 [5.3.6.2]
- Blaak G., Sparnaaij L.D. & Menendez T. (1963) Breeding and inheritance in the oil palm (*Elaeis guineensis* Jacq.) Part II. Methods of bunch quality analysis. *J.W. Afr. Inst. Oil Palm Res.*, 4, 146–155 [5.2.4; 5.2.4.2]
- Blal B. & Gianinazzi-Pearson V. (1990) Interest of endomycorrhizae for the production of micropropagated oil palm clones. *Agric. Ecosyst. Environ.*, 29, 39–43 [6.2.1.3]
- Bleasdale J.K.A. (1967) Systematic designs for spacing experiments. *Expl. Agric.*, 3, 73–85 [9.3.3.1]
- Bloomfield C. & Powlson D.C. (1977) The improvement of acid sulphate soils for crops other than padi. *Malay. agric. J.*, 51, 62–76 [3.4.3.3]
- BLRS (2002). *Annual Research Report*, 2001. Bah Lias Res. Sta., North Sumatra [4.1.3.2; 4.1.3.3]
- Boatman S.G. & Crombie W.M. (1958) Fat metabolism in the West African oil palm (*Elaeis guineensis*). 2. Fatty acid metabolism in the developing seedling. *J. Exp. Bot.*, 9, 52–74 [2.2.1.2]
- Bonhomme R. (2000) Beware of comparing RUE values calculated from PAR vs solar radiation or absorbed vs intercepted radiation. *Field Crop Res.*, 68, 247–252 [4.1.4.3]
- Bos I. & Sparnaaij L.D. (1993) Component analysis of complex characters in plant breeding. II. The pursuit of heterosis. *Euphytica*, 70, 237–245 [5.3.2]
- Bosshart R.P., Zaharah A.R. & Sharifuddin H.A.H. (1990) Proposal to include soil analysis as a diagnostic tool for fertilisation of oil palm in Malaysia. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani et al.), pp. 375–382, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.5.1]
- Bouharmont P. (1959) La culture d'embryons d'*Elaeis guineensis* Jacq. *Agricultura, Louvain*, 7, 297–323 [7.1.1.1]
- Bould C., Hewitt E.J. & Needham P. (1983) *Diagnosis of mineral disorders in plants – principles*, HMSO, London [11.4.1.1; 11.4.2.2]
- Bouma J. (1989) Using soil survey data for quantitative land evaluation. *Adv. Soil Sci.*, 9, 199–214 [8.1.5.1]
- Boyd D.A., Tinker P.B., Draycott A.P. & Last P. (1970) Nitrogen requirement of sugar beet grown in mineral soils. *J. agric. Sci., Camb.*, 74, 37–46 [11.3.1]
- Boyé P. & Aubry M. (1973) Replantation des palmeraies industrielles. Méthode de préparation de terrain et de protection

- contre l'*Oryctes* en Afrique de l'Ouest. *Oléagineux*, **28**, 175–176 [12.2.4.1]
- Braconnier S. & d'Auzac J. (1985) Anatomical study and cytological demonstration of potassium and chlorine flux associated with oil palm and coconut stomatal opening. *Oléagineux*, **40**, 547–551 [11.4.5.1]
- Braconnier S. & d'Auzac J. (1990) Chloride and stomatal conductance in coconut. *Pl. Physiol. Biochem.*, **28**, 105–111 [11.4.5.1]
- Bray R.H. (1954) A nutrient mobility concept of soil-plant relationships. *Soil Sci.*, **78**, 9–22 [11.3.1]
- Brédas J. & Scuvie L. (1960) Aperçu des influences climatiques sur les cycles de production du palmier à huile. *Oléagineux*, **15**, 211–222 [4.2.2.3; 4.4.3.2; 4.4.5.2; 4.4.7; 4.5.1]
- Brédas J., Stessels L. & Gérard P. (1968) La lutte chimique contre les petits rongeurs en jeune palmeraie. *Oléagineux*, **23**, 15–17 [12.3.1]
- Breure C.J. (1977) Preliminary results from an oil palm density × fertiliser experiment on young volcanic soils in West New Britain. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 192–207, Incomp. Soc. Planters, Kuala Lumpur [4.3.1; 4.3.2; 9.3.1]
- Breure C.J. (1985) Relevant factors associated with crown expansion in oil palm (*Elaeis guineensis* Jacq.). *Euphytica*, **34**, 161–175 [4.3.8.1; 5.4.4]
- Breure C.J. (1986) Parent selection for yield and bunch index in the oil palm in West New Britain. *Euphytica*, **35**, 65–72 [5.4.4]
- Breure C.J. (1988a) The effect of palm age and planting density on the partitioning of assimilates in oil palm (*Elaeis guineensis* Jacq.). *Expl Agric.*, **24**, 53–66 [4.1.4.3; 4.3.1; 4.3.5.2; 4.5.5; 9.3.1]
- Breure C.J. (1988b) The effect of different planting densities on yield trends in oil palm. *Expl Agric.*, **24**, 37–52 [4.1.4.2; 4.3.1.3; 4.3.5.1; 9.3.1; 9.3.3; 9.3.6.2]
- Breure C.J. (1994) Development of leaves in oil palm (*Elaeis guineensis* Jacq.) and the determination of leaf opening rates. *Expl Agric.*, **30**, 467–472 [4.2.1.1; 4.4.3.1]
- Breure C.J. (1998) *Origin of ASD's oil palm genetic material introduced in Indonesia and method of parent selection*. Paper presented at Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali [5.1.6.2; 5.4.5.2]
- Breure C.J. (2002) The search for yield of oil palm: basic principles. In: *The oil palm: management for large and sustainable yields* (Ed. by T.H. Fairhurst & R. Härdter), Potash & Phosphate Institute of Canada (ESEAP), Singapore [9.3.3.1; 9.3.6.2]
- Breure C.J. & Bos I. (1992) Development of elite families in oil palm (*Elaeis guineensis* Jacq.). *Euphytica*, **64**, 99–112 [5.3.3.2; 5.3.4.1; 6.5.3]
- Breure C.J. & Corley R.H.V. (1983) Selection of oil palms for high density planting. *Euphytica*, **32**, 177–186 [5.2.5; 5.3.4.1; 5.4.4; 6.4.1; 9.3.5]
- Breure C.J. & Corley R.H.V. (1992) Fruiting activity, growth and yield of oil palm. II Observations in untreated populations. *Expl Agric.*, **28**, 111–121 [4.4.2.2; 4.4.7.3; 4.5.3]
- Breure C.J. & Konimor J. (1992) Parent selection for oil palm clonal seed gardens. In: *Proc. Workshop 'Yield potential in the oil palm'* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 122–144, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2.2; 5.4.2.4; 5.5.1.1]
- Breure C.J. & Menendez T. (1990) The determination of bunch yield components in the development of inflorescences in oil palm (*Elaeis guineensis* Jacq.). *Expl Agric.*, **26**, 99–115 [4.4.4; 4.4.5; 4.4.7.3; 4.4.8]
- Breure C.J. & Powell M.S. (1988) The one-shot method of establishing growth parameters in oil palm. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 203–209, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.1.3.5]
- Breure C.J. & Rosenquist E.A. (1977) An oil palm fertilizer experiment on volcanic soils in Papua New Guinea. *Oléagineux*, **32**, 301–310 [11.4.5.1]
- Breure C.J. & Soebagyo F.X. (1991) Factors associated with occurrence of crown disease in oil palm (*Elaeis guineensis* Jacq.) and its effect on growth and yield. *Euphytica*, **54**, 55–64 [12.1.5.1]
- Breure C.J. & Verdooren L.R. (1995) Guidelines for testing and selecting parent palms in oil palm. Practical aspects and statistical methods. *ASD Oil Palm Papers*, **9**, 1–101 [4.1.3.5; 5.2.2; 5.2.3; 5.2.6.3]
- Breure C.J., Menendez T. & Powell M.S. (1990) The effect of planting density on the yield components of oil palm (*Elaeis guineensis* Jacq.). *Expl Agric.*, **26**, 117–124 [4.3.1.3; 4.4.5.1; 4.4.7; 9.3.1; 9.3.3.2]
- Breure C.J., Cahyono J. & Puspitaningrum Y. (2002) *Preliminary results of ASD's genetic material planted at PT. Bina Sawit Makmur seed garden of Selapan Jaya Group in South Sumatra*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [5.5.1.2]
- Bridge P.D., Panchal G., Sanderson F.R. & Pilotti C.A. (2001) Environmental sampling for *Ganoderma* in oil palm: a molecular tool for elucidating epidemiology. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 649–652, Malaysian Palm Oil Board, Kuala Lumpur [12.1.6.3]
- British Patent 1104577 (1968) *Process for extracting oil from palm fruits and olives* [13.4.3.5]
- Broekmans A.F.M. (1957a) The production of improved oil palm seed in Nigeria. *J. W. Afr. Inst. Oil Palm Res.*, **2**, 116–132 [5.4.1.2]
- Broekmans A.F.M. (1957b) Growth, flowering and yield of the oil palm in Nigeria. *J. W. Afr. Inst. Oil Palm Res.*, **2**, 187–220 [2.2.1.4; 4.2.1.1; 4.4; 4.5.1; 4.5.4]
- Broughton W.J. (1977) Effect of various covers on the performance of *Elaeis guineensis* (Jacq.) on different soils. In: *International developments in oil palm*, (Ed. by D.A. Earp & W. Newall), pp. 501–525, Incomp. Soc. Planters, Kuala Lumpur [10.1.2.3]
- Buchanan A.G. (1999) *Molecular genetic analysis of Fusarium wilt resistance in oil palm*. Thesis, Univ. of Bath, Bath [5.3.5; 12.1.6.2]
- Bucher H. & Fickendey E. (1919) *Die Olpalme*, Auswartigesamt, Berlin [7.1.1.1]
- Budiani A., Tahardi J.S. & Moller C. (1998) Oil palm protoplast isolation and culture. In: *Proc. BTIG Workshop 'Oil palm improvement through biotechnology'* (Ed. by J.S. Tahardi *et al.*), pp. 33–41, Biotechnology Research Unit for Estate Crops, Bogor, Indonesia [6.6.1.2; 11.4.1.3]
- Bull R.A. (1954) A preliminary list of oil palm diseases encountered in Nigeria. *J. W. Afr. Inst. Oil Palm Res.*, **1** (2), 53–93 [11.4.1.2; 12.1.4; 12.1.5.5; 12.1.6.3; 12.1.8]
- Bull R.A. (1961a) Studies on the deficiency diseases of the oil palm. 2. Macronutrient deficiency symptoms in oil palm seedlings grown in sand culture. *J. W. Afr. Inst. Oil Palm Res.*, **3**, 254–264 [11.4.1.1; 11.4.1.2; 12.1.5.2]

- Bull R.A. (1961b) Studies on the deficiency diseases of the oil palm. 3. Micronutrient deficiency symptoms in oil palm seedlings grown in sand culture. *J. W. Afr. Inst. Oil Palm Res.*, 3, 265–272 [11.4.1.1; 11.4.1.2; 11.8.5]
- Bull R.A. & Robertson J.S. (1959) The problems of 'little leaf' of oil palms – a review. *J. W. Afr. Inst. Oil Palm Res.*, 2, 355–375 [11.8.5; 12.1.7.1]
- Burkill I.H. (1966) *A dictionary of the economic products of the Malay Peninsula*, 2nd edn, Ministry of Agriculture & Cooperatives, Malaysia, Kuala Lumpur [5.1.1.1]
- Burns I.G. (1974) A model for predicting the redistribution of salts applied to fallow soil after excess rainfall or evaporation. *J. Soil Sci.*, 25, 165–178 [11.6.2.4]
- Buyckx E.J.E. (1952) Insectes et autres animaux nuisibles à l'*Elaeis guineensis* Jacq. In: *Notions de culture de l'Elaeis au Congo Belge* (Ed. by R. Vanderweylen), pp. 151–187, Direction de l'Agriculture, des Forêts, des Elevages et de la Colonisation, Brussels [12.2.3.1; 12.2.4.3]
- Caliman J.P. (1992) Oil palm and water deficit: production, adapted cropping techniques. *Oléagineux*, 47, 205–216 [3.2.3; 10.1.2.3]
- Caliman J.P. & Southworth A. (1998) Effect of drought and haze on the performance of oil palm. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 250–274, Indonesian Oil Palm Res. Inst., Medan, Indonesia [3.2.2.3; 3.2.4; 4.5.2; 10.5.2; 11.3.2.1]
- Caliman J.P., Olivin J. & Dufour O. (1988) Degradation of sandy ferralitic soils in oil palm cultivation through acidification and compaction – correction methods. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 287–293, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.5.2.2; 8.1.3.6]
- Caliman J.P., Concret J., Olivin J. & Dufour F. (1990) Maintenance of physical soil fertility under oil palm in humid tropical regions. *Oléagineux*, 45, 103–110 [8.1.3.3; 8.1.3.6]
- Caliman J.P., Daniel C. & Tailliez B. (1994) Oil palm mineral nutrition. *Plantations, Recherche, Développement*, 1, 36–54 [3.5.2.2; 11.3.1; 11.3.3; 11.4.4.1; 11.4.4.2; 11.6.3]
- Caliman J.P., Hardianto J. & Ng M. (2001) Strategy for fertilizer management during low commodity price. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 295–312, Malaysian Palm Oil Board, Kuala Lumpur [11.3.2.3]
- Caliman J.P., Widodo T., Suyanto S. & Tailliez B. (2002a) *Importance of palm growth during immaturity and impact on yield at an early stage*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [8.3.1]
- Caliman J.P., Togatorop E., Martha B. & Samosir R. (2002b) Aerial fertilisation of oil palm. *Better Crops International*, 16(2), 10–14 [11.9.3]
- Campbell G.S. (1991) Simulation of water uptake by roots. In: *Modelling plant and soil systems*, (Ed. by J. Hanks & J.T. Ritchie), pp. 273–284, Agronomy Series 31, Amer. Soc. Agron., Madison, WI [3.2.2.2]
- Cardoso R.M.E. (1961) Podridao de raizes em dendezeiro. *Biologico*, 27, 246 [12.1.4]
- Carrero R. (1998) Pasado, presente y futuro de la palma de aceite en Venezuela. *Palmas (Bogota)*, 19 (Special no.), 96–97 [1.4.3.12]
- Carrière de Belgarric R. (1951) Notes sur la sélection du palmier à huile à Sumatra: résultats obtenus par la SocFin. *Oléagineux*, 6, 65–71 [5.1.1.1]
- Casson A. (2000) *The hesitant boom: Indonesia's oil palm sub-sector in an era of economic crisis and political change*. Centre for International Forestry Research, Jakarta [1.4.3.1; 1.5.4; 3.3.2; 8.3.1; 15.3.2]
- Castilho A., Vershinin A. & Heslop-Harrison J.S. (2000) Repetitive DNA and the chromosomes in the genome of oil palm (*Elaeis guineensis*). *Ann. Bot.*, 85, 837–844 [2.2.1.6; 5.2.8.1]
- Caudwell R.W. (2000) Integrated management of insect pests (Orthoptera: Tettigoniidae) of oil palm in Papua New Guinea. *Planter, Kuala Lumpur*, 76, 393–407 [12.2.5.4]
- Chaidamsari T., Tahardi J.S. & Santoso D. (1998) *Agrobacterium*-mediated transformation in leaf explants oil palm. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 602–612, Indonesian Oil Palm Res. Inst., Medan, Indonesia [6.6.2.3]
- Chan K.S. (1977) Sampling of oil palm fruit bunch stalk refuse to determine oil loss. In: *Proc. Int. Symp. 'Palm oil processing and marketing'*, Incomp. Soc. Planters, Kuala Lumpur [13.4.5.2]
- Chan K.S. & Chew P.S. (1984) Volatilisation losses of urea on various soils under oil palm. In: *Proc. Seminar 'Fertilisers in Malaysian agriculture'* (Ed. by Chew P.S. *et al.*), pp. 91–103, Malaysian Soc. Soil Sci. and Universiti Pertanian Malaysia, Kuala Lumpur [11.6.2.6; 11.7.4.2]
- Chan K.S., Soh A.C. & Chew P.S. (1999) An accurate and precise method of determining oil to bunch in oil palm. *J. Oil Palm Res.*, 11, 11–22 [5.2.4.3]
- Chan K.W. (1972) *The effects of plant growth substances on fruit induction, development and fruit abscission in the oil palm (Elaeis guineensis Jacq.)*. Thesis, Univ. of Malaya, Kuala Lumpur [4.4.7.1]
- Chan K.W. (1977) A rapid method for studying the root distribution of oil palm and its application. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 131–151, Incomp. Soc. Planters, Kuala Lumpur [2.2.1.5]
- Chan K.W. (1979) Irrigation of oil palm in Malaysia. In: *Proc. Symp. 'Water in Malaysian agriculture'* (Ed. by E. Pushparajah), pp. 103–116, Malaysian Society of Soil Science, Kuala Lumpur [10.3]
- Chan K.W. (1991) *Predicting oil palm yield potential based upon solar radiation*. Paper presented at 2nd Natn. Seminar on Agrometeorology, Meteorological Dept. Malaysia, Petaling Jaya [3.2.4]
- Chan K.W. (1996) The economics of environmental protection and sustainable crop management practices in the oil palm industry. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 181–203, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.2.1]
- Chan K.W. (1999) Biomass production in the oil palm industry. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 41–53, Malaysian Oil Palm Growers' Council, Kuala Lumpur [11.6.1.1; 13.4.1]
- Chan K.W. (2000a) Soils management for sustainable oil palm cultivation. In: *Advances in oil palm research*, Vol. I (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), Malaysian Palm Oil Board, Kuala Lumpur [11.6.1.2; 11.7.5]
- Chan K.W. (2000b) The development, application and implication of ISO 14000 series of environmental management standards on the palm oil and related businesses. In: *Plantation tree crops in the new Millennium: the way ahead* (Ed. by E. Pushparajah), p. 887–905, Incomp. Soc. Planters, Kuala Lumpur [1.5.4; 15.3.2]

- Chan K.W. (2002) *Carbon sequestration and carbon accounting: our global strength*. Paper presented at Conf. 'R and D for competitive edge in the Malaysian oil palm industry', Malaysian Palm Oil Board, Kuala Lumpur. [15.3.2]
- Chan K.W. & Lim K.C. (1982) Quantification of the effects of legume establishment and maintenance on yield of oil palm. In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 301–314, Incomp. Soc. Planters, Kuala Lumpur [8.4.2]
- Chan K.W., Yee C.B., Lim K.C. & Goh M. (1985) Effect of rain-fall and irrigation on oil palm yield production. In: *Proc. Natn. Conf. 'Soil-climate relationships on crop production in Malaysia'* (Ed. by Mok C.K., Lim K.H. & Azmi Mad Akhir), pp. 43–67, Malaysian Soc. Soil Sci. Kuala Lumpur [4.5.3; 10.3]
- Chan K.W., Ong E.C., Tan K.S., Lee C.H. & Law I.H. (1986) The performance of Oil Palm Genetic Laboratory (OPGL) germplasm material. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 162–174, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.2; 5.5.1.7]
- Chan K.W., Yong Y.Y., Ahmad Alwi & Goh K.H. (1988) Comparison of the yield, bunch and oil characteristics and their heritabilities before and after the introduction of pollinating weevils (*E. kamerunicus*) in the oil palm (*E. guineensis*) in Malaysia. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 557–567, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.3.2]
- Chan K.W., Lim K.C. & Alwi A. (1993) Fertiliser efficiency studies in oil palm. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 302–311, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.6.1.3]
- Chan K.W., Basiron Y. & Chin C.W. (1999) Challenges facing the oil palm industry – the plantation perspective. *Palm Oil Dev.*, 31, 7–19 [1.4.3.2; 1.5.4]
- Chan K.W., Tarmizi A. & Wahid Omar (2000) Advances in fertiliser management in the oil palm industry. *Oil Palm Bull.*, 41, 39–46 [11.4.1.1]
- Chander Rao S. (1997) Some observations on stem wet rot disease of oil palm (*Elaeis guineensis*) in Andhra Pradesh, India. *Planter, Kuala Lumpur*, 73, 611–614 [12.1]
- Chandrasekharan K. & Edmunds G.C. (1976) Porcupine – a major pest in oil palm clearing from jungle in Central Johore. *Planter, Kuala Lumpur*, 52, 216–225 [12.3.2]
- Chang K.C. & Zakaria Abas (1986) Leaching losses of N and K fertilisers from mature fields of perennial crops in Malaysia – a review of local work. *Planter, Kuala Lumpur*, 62, 468–487 [11.7.4.1]
- Chang K.C., Foster H.L. & Abas Z. (1988) Monthly frond production of oil palm in Malaysia. *Oléagineux*, 43, 439–444 [4.4.3.1]
- Chang K.C., Rao V., Hasmuddin M.Y. & Zakaria A. (1995) Inflorescence abortion and flowering cycles in oil palm. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 519–524, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.4.5.4; 4.4.8]
- Chapas L.C., Tinker P.B. & Ziboh C.O. (1957) The determination of the oil content of oil palm fruit. *J. W. Afr. Inst. Oil Palm Res.*, 2, 230–236 [5.2.4.2]
- Chapman K.R., Escobar R. & Griffie P. (2001) Cold tolerant (CT) or altitude adapted oil palm hybrid development initiatives in the Asia/Pacific region. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 282–288, Malaysian Palm Oil Board, Kuala Lumpur [3.2.1]
- Cheah S.C. & Hoi W.K. (1999) By-products for chemical, micro-biological and other uses. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 241–252, Malaysian Oil Palm Growers' Council, Kuala Lumpur [13.4.8.2; 13.6.1.3]
- Cheah S.C. & Wooi K.C. (1995) Application of molecular marker techniques in oil palm tissue culture. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 163–170, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.1.2]
- Cheah S.C., Siti Nor Akmar A., Ooi L.C.L., Rahimah A. Rahman & Madon M. (1993) Detection of DNA variability in the oil palm using RFLP probes. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 144–150, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.3]
- Cheah S.C., Madon M. & Singh R. (2000) Oil palm genomics. In: *Advances in oil palm research*, Vol. I (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 332–370, Malaysian Palm Oil Board, Kuala Lumpur [2.2.1.6]
- Chee C.F., Chuah J.H., Lim K.H. & Ho C.Y. (1995) Preliminary results of oil palm terracing and platforming trials on steep terrains. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 245–252, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.5]
- Chee K.H. & Chiu S.B. (1999) Fruit waste recycling by mulching with empty fruit bunches. *Planter, Kuala Lumpur*, 75, 435–442 [10.2.1]
- Chee K.H., Chiu S.B. & Chan S.M. (1997) Pre-nursery seedlings grown on pot trays. *Planter, Kuala Lumpur*, 73, 295–299 [7.2.1]
- Chen C.P. & Baker M.J. (1993) Pastures as the secondary component in tree-pasture systems. In: *Grasslands for our world*, pp. 756–762, SIR Publishing, Wellington, New Zealand [8.4.3.4]
- Chevalier A. (1910) Les végétaux utiles de l'Afrique tropicale française, Vol. 7. *Documents sur le palmier à huile*. Challamel, Paris [2.2]
- Chevalier A. (1934) La patrie des divers *Elaeis*, les espèces et les variétés. *Rev. Bot. appl. Agric. trop.*, 14, 187–196 [1.1.3]
- Chew J.S. & Abdul Rahim A. (2000) Practical mapping of oil palm yield using GPS and GIS technologies. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 793–806, Incomp. Soc. Planters, Kuala Lumpur [10.7.5]
- Chew J.S., Gan L.T., Chew O.K. & Yeoh O.T. (1996) Mechanically assisted in-field collection (MAIC) – Sime Darby's approach and experiences. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 280–293, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.4.6]
- Chew P.S. (1996) Industry's low OER problems – impact, outlook and implications. *Planter, Kuala Lumpur*, 72, 273–290 [4.5.2; 10.5.3]
- Chew P.S. (1998) Prospects for precision plantation practices in oil palm. *Planter, Kuala Lumpur*, 74, 661–684 [10.2; 10.4.6; 10.7.5]
- Chew P.S. (2001) *Management issues in oil palm plantations R and D in Malaysia*. Paper presented at 2001 Int. Palm Oil Congr. – Agriculture, Malaysian Palm Oil Board, Kuala Lumpur, 20–22 Sept. [1.5.4]
- Chew P.S. & Khoo K.T. (1973) Early results from disbudbing trials on oil palms. In: *Advances in oil palm cultivation* (Ed. by

- R.L. Wastie & D.A. Earp), pp. 133–146, Incomp. Soc. Planters, Kuala Lumpur [10.4.2]
- Chew P.S. & Khoo K.T. (1977) Growth and yield of intercropped oil palms on a coastal clay soil in Malaysia. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 541–553, Incomp. Soc. Planters, Kuala Lumpur [10.1.4]
- Chew P.S. & Pushparajah E. (1995) Nitrogen management and fertilisation of tropical plantation tree crops. In: *Nitrogen fertilisation in the environment*, (Ed. by P.E. Bacon), Marcel Dekker, New York [11.9.2.2]
- Chew P.S., Kee K.K., Goh K.J., Quah Y.T. & Tey S.H. (1992) Fertiliser management in oil palms. In: *Proc. Int. Conf. Fertiliser usage in the tropics* (Ed. by B. Abu Talib *et al.*), pp. 43–67, Kuala Lumpur [8.1.3.6; 11.6.4.3; 11.7.4.2; 11.9.2.1]
- Chew P.S., Soh A.C., Goh K.J. & Kee K.K. (1998) Role of private sector research in oil palm crop production. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 133–144, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.5.4, 11.3.3.1; 15.1]
- Cheyns E., Kouamé Y.S. & Nai Nai S. (2001) Itinéraires techniques et nature du matériel végétal: diversité des formes sociales et techniques de production en Côte d'Ivoire. *Ol Corps Gras Lipides*, 8, 524–528 [5.1.5; 13.6.2]
- Chia C.C., Lim C.C., Teo K.W. & Rao V. (2002) Oil palm replanting – experiences of underplanting. *Planter, Kuala Lumpur*, 78, 237–248 [8.3.4.3]
- Chia T.H., Lim J.L. & Buckle A. (1995) Barn owls for rat control in oil palm plantations – do they work? *Planter, Kuala Lumpur*, 71, 109–117 [12.3.1]
- Chikwe J.E. (1995) A comparative analysis of mechanised and manual modes of land preparation in the establishment of a unit area of oil palm plantation in Nigeria. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 595–602, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.3.1]
- Chin C.W. (1982) Segregation of fertility, fruit forms and early yield performance of selected sibbed and outcrossed fertile *pisifera* progenies. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 63–68, Incomp. Soc. Planters, Kuala Lumpur [5.5.1.5]
- Chin C.W. (1988) Outlook on fertile *pisifera* breeding. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 107–111, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.2; 5.3.3.1; 5.3.3.2; 5.5.1.5]
- Chin C.W. (1992) Performance of D × P and D × T crosses from various origins on inland areas of Peninsular Malaysia. In: *Proc. Workshop 'Yield potential in the oil palm'* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 1–10, Int. Soc. Oil Palm Breeders, Kuala Lumpur [5.5.1.3]
- Chin C.W. (1993) Progress and prospects of *oleifera* hybrids and backcrosses in breeding. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 557–563, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.6]
- Chin C.W. (1995) Felda's experience with fertile *pisifera* breeding. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 489–501, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.5]
- Chin C.W. (1999) Oil palm breeding techniques. In: *Proc. Seminar 'Science of oil palm breeding'* (Montpellier, 1992) (Ed. by N. Rajanaidu & B.S. Jalani), pp. 49–64, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2; 5.2.1.2]
- Chin C.W. & Shuhaimi S. (1999) Felda oil palm planting materials. In: *Proc. 1996 Seminar 'Sourcing of oil palm planting materials for local and overseas joint ventures'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 71–90, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.2; 5.1.6.2]
- Chin C.W. & Shuhaimi S. (2000) *Utilisation of PORIM's Nigerian germplasm as potential planting materials in FELDA Agricultural Services Sdn Bhd (FASSB)'s breeding programme*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June 2000, Malaysian Palm Oil Board, Kuala Lumpur [5.1.7.4]
- Chin C.W. & Tang T.L. (1979) The oil palm – fertile *pisifera*. *Planter, Kuala Lumpur*, 55, 64–77 [5.5.1.5]
- Chinchilla C.M. & Duran N. (1999) Nature and management of spear rot-like problem in oil palm: a case study in Costa Rica. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 97–126, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.7.2]
- Chinchilla C.M. & Richardson D.L. (1990) Polinización en palma aceitera (*Elaeis guineensis* Jacq.) en Centroamérica 1. Población de insectos y conformación de racimos. *Turrialba*, 40, 452–460 [2.2.2.5]
- Chinchilla C.M., Umaña C.H. & Richardson D.L. (1990) Material de desarrollo avanzado en viveros de palma aceitera (*Elaeis guineensis* Jacq.) 1. Espaciamiento y volumen de bolsa. *Turrialba*, 40, 428–439 [7.2.3]
- Chinchilla C.M., Oehlschlager A.C. & Gonzalez L.M. (1995) Management of red ring disease in oil palm through pheromone-based trapping of *Rhynchophorus palmarum* (L.). In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 428–441, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.6; 12.2.6.1]
- Chinchilla C.M., Oehlschlager C. & Bulgarelli J. (1996) A pheromone based trapping system for *Rhynchophorus palmarum* and *Metamasius hemipterus*. *ASD Oil Palm Papers*, 12, 11–17 [12.1.6.6]
- Chiu S.B., Khoo K.C. & Mohd Yusof Hussein (1985) Extent of rat predation on *Elaeidobius kamerunicus* Faust, the pollinating weevil of oil palm. *Planter, Kuala Lumpur*, 61, 101–112 [12.5.1]
- Chong C.L. (2000) Storage, handling and transportation of palm oil and palm oil products. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 806–844, Malaysian Palm Oil Board, Kuala Lumpur [13.4.3.6; 13.4.6.1; 13.4.6.2]
- Choo Y.M. & Cheah K.Y. (2000) Biofuel. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 1293–1345, Malaysian Palm Oil Board, Kuala Lumpur [14.3.6.2]
- Chooi C.F. (1983) Sterilised palm fruit bunch threshing. In: *Proc. Regional Workshop 'Palm oil mill technology and effluent treatment'*, pp. 17–27, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.3.3]
- Choong C.Y., Shah F.H., Rajanaidu N. & Zakri A.H. (1996) Isoenzyme variation of Zairean oil palm (*Elaeis guineensis* Jacq.) germplasm collection. *Elaeis*, 8, 45–53 [5.2.8.1]
- Chow C.S. (1992a) A model for explaining variations in oil palm yield on field or estate basis. In: *Proc. Workshop 'Yield potential in the oil palm'* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 154–167, Inst. Soc. Oil Palm Breeders, Kuala Lumpur [4.5.3]

- Chow C.S. (1992b) The effects of season, rainfall and cycle on oil palm yield in Malaysia. *Elaeis*, **4** (1), 32–43 [3.3.1]
- Chowdhury M.K.U. (1995) Detection of variation in tissue culture-derived normal and abnormal clones of oil palm using RAPD method. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 190–194, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.1.2]
- Christensen S. and Tiedje J.M. (1988). Denitrification in the field, analysis of spatial and temporal variability. In *Nitrogen efficiency in agricultural soils*. (Ed. by D.S. Jenkinson and K.A. Smith). pp. 295–301. Elsevier Applied Science, London [11.7.4.2]
- Chua K.L., Singh R. & Cheah S.C. (2001) Construction of oil palm (*Elaeis guineensis* Jacq.) linkage maps using AFLP markers. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 461–465, Malaysian Palm Oil Board, Kuala Lumpur [5.2.8.3]
- Chuah J.H. & Lim K.H. (1989) Water management of oil palm on coastal soils – Sime Darby's experience. *Planter*, Kuala Lumpur, **65**, 334–344 [3.5.1.1; 8.2.3; 10.3; 10.3.1.2]
- Chung G.F. (1997) The bioefficacy of the aggregation pheromone in mass trapping of rhinoceros beetles (*Oryctes rhinoceros* L.) in Malaysia. *Planter*, Kuala Lumpur, **73**, 119–127 [12.2.4.1]
- Chung G.F. & Balasubramaniam R. (1996) The importance of weed control in the establishment of legume cover crops. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 492–498, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.1.2.3]
- Chung G.F. & Balasubramaniam R. (2000) Rat baiting techniques in oil palm estates facing labour shortage. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 515–528, Incomp. Soc. Planters, Kuala Lumpur [12.3.1]
- Chung G.F. & Sharma M. (1999) Integrated pest and disease management and associated impact of pesticides. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 83–111, Malay. Oil Palm Growers' Council, Kuala Lumpur [12.2.1]
- Chung G.F. & Sim S.C. (1993) Bagworm census and control – a case study. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 433–442, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.5.2]
- Chung G.F., Sim S.C., Hon K.M. & Ramli K. (1995) Monitoring and surveillance system for integrated pest management of leaf eating caterpillars in oil palm. *Planter*, Kuala Lumpur, **71**, 253–263 [12.2.1.3]
- Chung G.F., Cheah S.S. & Ramalingam B. (1999) Effects of pest damage during immature phase on the early yields of oil palm. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 454–476, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.1.2; 12.2.4.1]
- Clegg A.J. (1973) An analysis of damage incurred by oil palm bunches during handling and transport. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 421–431, Incomp. Soc. Planters, Kuala Lumpur [13.4.6.1]
- Clendon J.H. (1990) The need for mechanisation on oil palm estates. *Planter*, Kuala Lumpur, **66**, 412–419 [10.4.5]
- Cochard B., Noiret J.M., Baudouin L., Flori A. & Amblard P. (1995) Second cycle of reciprocal recurrent selection (RRS) in oil palm, *Elaeis guineensis* Jacq. Results of Deli × La Mé hybrid tests. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 24–35, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.1]
- Cochard B., Durand-Gasselin T., Amblard P., Konan E. & Gogor S. (1999) Performance of adult oil palm clones. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 12–22, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.2; 5.3.3.2; 6.4.2]
- Cochard B., Durand-Gasselin T. & Adon B. (2000) *Oil palm genetic resources in the Côte d'Ivoire – composition, assessment and use*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.1.3.1; 5.1.7.1; 5.1.7.4]
- Comstock R.E. & Robinson H.F. (1952) Estimation of average dominance of genes. In: *Heterosis* (Ed. by J.W. Gowen), pp. 494–516, Iowa State College Press, Iowa [5.2.2]
- Cook O.F. (1942) A Brazilian origin for the commercial oil palm. *Sci. Monthly*, **54**, 577–580 [1.1.1]
- Cooke G.W. (1967) *The control of soil fertility*, Crosby Lockwood, London [11.6.1.1]
- Cooper I.W. (1983) Boiler operation. In: *Proc. Regional Workshop 'Palm oil mill technology and effluent treatment'*, pp. 48–57, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.1]
- Cooper R.M., Flood J. & Mepsted R. (1989) *Fusarium wilt of oil palm: transmission, isolate variation, resistance*. In: *Vascular wilt diseases of plants, NATO ASI Series*, Vol. H-28 (Ed. by E.C. Tjamos & C.H. Beckman), pp. 247–258, Springer, Berlin [12.1.6.2]
- Corley R.H.V. (1973a) Oil palm physiology: a review. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 37–51, Incomp. Soc. Planters, Kuala Lumpur [4.4.4.3; 4.4.5.3; 4.4.6; 4.4.7.3; 5.6; 11.3.2.4]
- Corley R.H.V. (1973b) Effects of plant density on growth and yield of oil palm. *Expl. Agric.*, **9**, 169–180 [3.2.4; 3.3.1; 4.1.4.2; 4.2.1; 4.3.1; 4.4.7.1; 5.3.4.1; 5.4.4; 9.3.3.1; 9.3.4]
- Corley R.H.V. (1976a) Effects of severe leaf pruning on oil palm, and its possible use for selection purposes. *Malay. agric. Res. Dev. Inst. Res. Bull.*, **4**(2), 23–28 [4.2.1; 4.3.6.3; 5.4.4]
- Corley R.H.V. (1976b) Sex differentiation in oil palm: effects of growth regulators. *J. exp. Bot.*, **27**, 553–558 [4.4.4.2]
- Corley R.H.V. (1976c) Photosynthesis and productivity. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 55–76, Elsevier, Amsterdam [3.2.4; 4.1.4; 4.2.2.4; 4.3.2.2; 4.3.6.1]
- Corley R.H.V. (1976d) Inflorescence abortion and sex differentiation. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 37–54, Elsevier, Amsterdam [4.4.1; 4.4.3.2; 4.4.4; 4.4.5]
- Corley R.H.V. (1976e) Physiological aspects of nutrition. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 157–164, Elsevier, Amsterdam [11.1.2]
- Corley R.H.V. (1976f) Planting density. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 273–283, Elsevier, Amsterdam [9.3.3.1; 9.3.3.2]
- Corley R.H.V. (1976g) Germination and seedling growth. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 23–36, Elsevier, Amsterdam [2.2.1.2]
- Corley R.H.V. (1977a) Oil palm planting density and thinning of mature plantings. *Planter*, Kuala Lumpur, **53**, 349–359 [9.3.6.2]
- Corley R.H.V. (1977b) Oil palm yield components and yield cycles. In: *International developments in oil palm* (Ed. by D.A.

- Earp & W. Newall), pp. 116–129, Incomp. Soc. Planters, Kuala Lumpur [4.4; 4.4.8]
- Corley R.H.V. (1979) Palm oil composition and oil palm breeding. *Planter, Kuala Lumpur*, 55, 467–478 [5.3.7]
- Corley R.H.V. (1980) Vegetative propagation of palms. In: *Sago. The equatorial swamp as a natural resource* (Ed. by W.R. Stanton & M. Flach), pp. 98–109, Martinus Nijhoff, The Hague [6.4.3.2]
- Corley R.H.V. (1983a) Photosynthesis and age of oil palm leaves. *Photosynthetica*, 17, 97–100 [4.3.6.2]
- Corley R.H.V. (1983b) Potential productivity of tropical perennial crops. *Expl Agric.*, 19, 217–237 [5.6; 10.7.1]
- Corley R.H.V. (1985) Yield potentials of plantation crops. In: *Potassium in the agricultural systems of the humid tropics, Proc. 19th Colloquium Int. Potash Inst.*, pp. 61–80, Int. Potash Inst., Berne [4.3.2; 10.7.1]
- Corley R.H.V. (1986) Oil palm. In: *CRC handbook of fruit set and development* (Ed. by S.P. Monselise), pp. 253–259, CRC Press, Boca Raton, Florida [4.2.2.3; 4.4.2.1]
- Corley R.H.V. (1992) Yield potential in Colombia. In: *Proc. Workshop 'Yield potential in the oil palm'* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), p. 217, Int. Soc. Oil Palm Breeders, Kuala Lumpur [1.4.3.9; 10.3]
- Corley R.H.V. (1993) Fifteen years experience with oil palm clones – a review of progress. In: *Proc. Int. Oil Palm Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 69–81, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.1; 6.2.1.3; 6.3.1.1; 6.3.3; 6.4.3.1; 11.2.2; 12.1.6.2]
- Corley R.H.V. (1996) Irrigation of oil palms – a review. *J. Plantation Crops*, 24 (Suppl.), 45–52 [10.3.2.1]
- Corley R.H.V. (1998) What is the upper limit to oil extraction ratio? In: *Proc. 1996 Int. Conf. 'Oil and kernel production in oil palm – a global perspective'* (Ed. by N. Rajanaidu, I.E. Henson & B.S. Jalani), pp. 256–269, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2.4; 5.6]
- Corley R.H.V. (2001) Oil palm. In: *Ecosystems of the world 19 – Tree crop ecosystems* (Ed. by F.T. Last), pp. 299–320, Elsevier, Amsterdam [10.1.2.3; 10.5.2]
- Corley R.H.V. & Breure C.J. (1981) *Measurements in oil palm experiments*, Internal Report, Unilever Plantations, London [4.1.3.1]
- Corley R.H.V. & Breure C.J. (1992) Fruiting activity, growth and yield of oil palm. I. Effects of fruit removal. *Expl Agric.*, 28, 99–109 [4.2.1; 4.2.2.2; 4.3.7; 4.4.2–5; 4.4.7]
- Corley R.H.V. & Donough C.R. (1992) Potential yield of oil palm clones – the importance of planting density. In: *Proc. Workshop 'Yield potential in the oil palm'* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 58–70, Int. Soc. Oil Palm Breeders, Kuala Lumpur [4.1.4.2; 4.2.1; 4.3.1; 4.3.8.1; 5.5.1.7; 6.4.3.3; 9.3.3; 9.3.3.1; 9.3.5]
- Corley R.H.V. & Gray B.S. (1976a) Growth and morphology. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 7–21, Elsevier, Amsterdam [2.2.1.4; 4.1.4.2; 4.2.1.1; 4.3.5.3]
- Corley R.H.V. & Gray B.S. (1976b) Yield and yield components. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 77–86, Elsevier, Amsterdam [2.2.2.1; 2.2.2.2; 2.2.2.7; 4.4.4; 4.4.7; 5.3.3.2]
- Corley R.H.V. & Hew C.K. (1976) Pruning. In: *Oil palm research*, (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 307–313, Elsevier, Amsterdam [4.4.4.1; 4.4.7.2]
- Corley R.H.V. & Hong T.K. (1982) Irrigation of oil palms in Malaysia. In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 343–346, Incomp. Soc. Planters, Kuala Lumpur [4.4.3.1; 4.4.4.1; 10.3]
- Corley R.H.V. & Law I.H. (1997) The future for oil palm clones. In: *Plantation management for the 21st century* (Ed. by E. Pushparajah), pp. 279–289, Incomp. Soc. Planters, Kuala Lumpur [6.4.2; 6.5.3]
- Corley R.H.V. & Law I.H. (2001) Ripening, harvesting and oil extraction. *Planter, Kuala Lumpur*, 77, 507–524 [10.4.4; 10.5.2]
- Corley R.H.V. & Lee C.H. (1992) The physiological basis for genetic improvement of oil palm in Malaysia. *Euphytica*, 60, 179–184 [4.3.8; 5.3.3.1; 5.3.3.2; 5.3.4.2; 5.5.2.2]
- Corley R.H.V. & Mok C.K. (1972) Effects of nitrogen, phosphorus, potassium and magnesium on growth of the oil palm. *Expl Agric.*, 8, 347–353 [4.1.4.2; 4.3.2]
- Corley R.H.V. & Stratford R. (1998) Biotechnology and oil palm: opportunities and future impact. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 80–91, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.4.4; 6.6.3]
- Corley R.H.V. & Teo C. (1976) Disbudding of mature oil palms as a method of controlling yield fluctuation. *Malay. agric. Res. Dev. Inst. Res. Bull.*, 4 (1), 1–6 [4.4.5.1; 4.5.1; 10.4.2]
- Corley R.H.V., Gray B.S. & Ng S.K. (1971a) Productivity of the oil palm (*Elaeis guineensis* Jacq.) in Malaysia. *Expl Agric.*, 7, 129–136 [4.1.1.1; 4.1.2; 4.1.3; 4.1.4; 4.2.1]
- Corley R.H.V., Hardon J.J. & Tan G.Y. (1971b) Analysis of growth of the oil palm (*Elaeis guineensis* Jacq.). 1. Estimation of growth parameters and application in breeding. *Euphytica*, 20, 307–315 [4.1.3; 4.3.8; 5.2.5; 5.3.4.1; 5.4.4; 11.6.2.3]
- Corley R.H.V., Hew C.K., Tam T.K. & Lo K.K. (1973a) Optimal spacing for oil palms. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 52–71, Incomp. Soc. Planters, Kuala Lumpur [5.4.4; 9.3.2; 9.3.3; 9.3.6.3]
- Corley R.H.V., Hardon J.J. & Ooi S.C. (1973b) Some evidence for genetically controlled variation in photosynthetic rate of oil palm seedlings. *Euphytica*, 22, 48–55 [4.3.8.2; 5.2.7]
- Corley R.H.V., Wooi K.C. & Wong C.Y. (1979) Progress with vegetative propagation of oil palm. *Planter, Kuala Lumpur*, 55, 377–380 [6.1]
- Corley R.H.V., Wong C.Y., Wooi K.C. & Jones L.H. (1982) Early results from the first oil palm clone trials. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 173–196, Incomp. Soc. Planters, Kuala Lumpur [6.3; 6.4.3.2]
- Corley R.H.V., Lee C.H., Law I.H. & Wong C.Y. (1986) Abnormal flower development in oil palm clones. *Planter, Kuala Lumpur*, 62, 233–240 [6.1; 6.3.1]
- Corley R.H.V., Lee C.H., Law I.H. & Cundall E. (1988) Field testing of oil palm clones. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 173–185, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2.3; 6.4; 6.4.2; 6.4.3.1; 6.5.3]
- Corley R.H.V., Tan Y.P., Timti I.N. & de Greef W. (1993) Yield of oil palm progenies in Zaire, Cameroun and Malaysia. In: *Proc. 1991 Int. Soc. Oil Palm Breeders Workshop 'Genotype–environment interaction studies in perennial tree crops'*, pp. 46–54, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.7]
- Corley R.H.V., Ng M. & Donough C.R. (1995a) Effects of defoli-

- ation on sex differentiation in oil palm clones. *Expl Agric.*, **31**, 177–189 [4.4.1; 4.4.3.2; 4.4.4.1; 4.4.4.3; 4.4.5]
- Corley R.H.V., Boonrak T., Donough C.R., Nelson S., Dumortier F., Soebagiyo F.X. & Vallejo G. (1995b) Yield of oil palm clones in different environments. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 145–157, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.7; 6.4.3.1]
- Cornaire B., Houssou M. & Meunier J. (1989) *Breeding for drought resistance in the oil palm 2. Kinetics of stomatal opening and protoplasmic resistance*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov, Nigerian Inst. Oil Palm Res., Benin City [5.3.6.1]
- Cornaire B., Daniel C., Zuily-Fodil Y. & Lamade E. (1994) Oil palm performance under water stress. Background to the problem, first results and research approaches. *Oléagineux*, **49**, 1–11 [3.5.2.2; 5.3.6.1]
- Cornelius J.A. (1983) *Processing of oil palm fruit and its products*, Tropical Products Inst., London [13.4.3.5]
- Corner E.J.H. (1966) *The natural history of palms*, Weidenfeld and Nicolson, London [1.1.1]
- Corrado F. (1970) La maladie du palmier à huile dans les Llanos de Colombie. *Oléagineux*, **25**, 383–384 [12.1.6.4]
- Corrado F. (1985) Conformation of oil palm bunches (*Elaeis guineensis* Jacq.) in certain Colombian plantations. *Oléagineux*, **40**, 173–187 [2.2.2.5]
- Corrado F. & Wuidart W. (1990) Germination of oil palm (*E. guineensis*) seeds in polythene bags. 'Dry heat' method. *Oléagineux*, **45**, 511–518 [7.1; 7.2.2.4]
- Corrado F., Quencez P. & Tailliez B. (1992) Boron deficiency in oil palm. Symptoms and corrections. *Oléagineux*, **47**, 719–725 [11.3.3.2; 11.4.1.3; 11.8.5]
- Cotterell G.S. (1925) The Hispid leaf miner (*Coelaenomenodera elaeidis* Maul) of oil palms (*Elaeis guineensis* Jacq.) on the Gold Coast. *Bull. ent. Res.*, **16**, 77–83 [12.2.5.5]
- Cottrell R.C. (1991) Introduction: nutritional aspects of palm oil. *Amer. J. Clin. Nutr.*, **53** (Suppl.), 989S–1009S [14.4; 14.4.1]
- Courade G. (1978) Les plantations industrielles d'Unilever en Cameroun. *Cahiers d'ONAREST*, **1** (2), 91–159 [1.4.3.7]
- Courtois G. (1968) Arbres anormaux chez *Elaeis guineensis*. Leur production comparée à celle des arbres normaux. *Oléagineux*, **23**, 641–644 [12.1.9]
- Crombie W.M. (1956) Fat metabolism in the West African oil palm (*Elaeis guineensis*). 1. Fatty acid formation in the maturing kernel. *J. Exp. Bot.*, **7**, 181–193 [13.3.1]
- Crombie W.M. & Hardman E.E. (1958) Fat metabolism in the West African oil palm (*Elaeis guineensis*). 3. Fatty acid formation in the maturing exocarp. *J. Exp. Bot.*, **9**, 247–253 [13.3.2]
- Crone G.R. (1937) The voyages of Cadamosto and other documents on Western Africa in the second half of the fifteenth century. *Hakluyt Society, Series II*, **80** [1.1.2]
- Cronquist A. (1981) *An integrated system of classification of flowering plants*. Columbia University Press [2.1]
- Dahlan I. & Shahar M.Z. (1992) Simulation models for quantitative decisions in crop livestock integrated farming systems. *J. Asian Farming Syst. Assoc.*, **1**, 351–360 [8.4.3.4]
- Dahlan I., Shamsul B.M.T. & Aidi M. (1997) Buffaloes as draught animal power in oil palm plantations. In: *Proc. 5th World Buffalo Congress*, (Ed. by A. Borghese, S. Failla & V.L. Barile), pp. 471–475, Caserta, Italy [10.4.5]
- Dahlan I., Islam M. & Rajion M.A. (2000) Nutrient intake and digestibility of fresh, ensiled and pelleted oil palm (*Elaeis guineensis*) frond by goats. *Asian Austr. J. Anim. Sci.*, **13**, 1407–1413 [13.6.3]
- Dalzell R. (1977) *Unipamol Malaysia Sdn Bhd Livestock pilot project, 1974–77*. Internal Unilever report [13.6.3]
- Dalzell R. (1978) A case study on the utilisation of effluent and by-products of oil palm by cattle and buffaloes on an oil palm estate. In: *Feeding stuffs for livestock in South East Asia* (Ed. by C. Devendra & R.I. Hutagalung), pp. 132–141, Malaysian Soc. Animal Production, Kuala Lumpur [13.6.3]
- Daniel C. & de Taffin G. (1974) Conduite des jeunes plantations de palmier à huile en zones sèches au Dahomey. *Oléagineux*, **29**, 227–232 [10.1.2.3]
- Davidson L. (1993) Management for efficient, cost-effective and productive oil palm plantations. In: *Proc. 1991 PORIM International Palm Oil Conference – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 153–167, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.4.3.2; 5.5.2; 10.1.5; 13.4.5.3; 14.2.1; 14.2.2]
- Davidson L. (1998) Progress of the oil palm industry. *Trop. Agric. Assoc. Newslett.*, **18** (1), 18–21 [1.4.2.4]
- Davila G.A., Guerrero R. & Rojas L.A. (1998) Availability of potassium in some oil palm soils of the eastern plains of Colombia. *Suelos Ecuatoriales*, **28**, 71–79 [11.5.1]
- Davila G.A., Guerrero R. & Rojas L.A. (2000a) Variation of available sulphur in soil and its foliar content in the adult African palm in the piedmont soils of the Colombian plains, during two climatic periods. *Suelos Ecuatoriales*, **30**, 29–35 [11.5.1]
- Davila G.A., Rojas L.A. & Guerrero R. (2000b) Leaf concentration of microelements in oil palm and its relation to their soil content in the Colombian eastern piedmont during two climatic periods. *Suelos Ecuatoriales*, **30**, 36–43 [11.5.1]
- Davis T.A. (1980) Double reversal of spadices in an African oil palm. *Planter, Kuala Lumpur*, **56**, 212–216 [2.2.1.4]
- de Berchoux C. & Gascon J.P. (1963) L'arcure défoliée du palmier à huile – éléments pour l'obtention de lignées résistantes. *Oléagineux*, **18**, 713–715 [5.3.5; 12.1.5.1]
- de Berchoux C. & Gascon J.P. (1965) Caractéristiques végétatives de cinq descendances d'*Elaeis guineensis* Jacq. – premières données biométriques – relations entre divers caractères et la production. *Oléagineux*, **20**, 1–7 [4.4.2; 4.5.3; 5.3.4]
- de Blank S. (1952) A reconnaissance of the American oil palm. *Trop. Agric., Trinidad*, **29**, 1–14 [2.3.1; 5.1.7.3]
- de Franqueville H. (1984) Vascular wilt of the oil palm: relationship between nursery and field resistance. *Oléagineux*, **39**, 513–518 [12.1.6.2]
- de Franqueville H. (1991) Former savannah or former forest: effect of pathogen isolates on the performance of oil palm families with respect to *Fusarium* wilt. *Oléagineux*, **46**, 179–186 [12.1.6.2]
- de Franqueville H. (2000) *Report on the plant pathology mission, Socfindo (Indonesia, Oil Palm)*. Internal report, CIRAD-CP [12.1.6.3]
- de Franqueville H. (2001) *Oil palm bud rot in Latin America – preliminary review of established facts and achievements*. Burotrop: <http://www.burotrop.org/palmmrot.htm> [12.1.7.2]
- de Franqueville H. & de Greef W. (1988) Hereditary transmission of resistance to vascular wilt of the oil palm: facts and hypotheses. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'*

- (Ed. by A. Halim Hassan *et al.*), pp. 118–129, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.5]
- de Franqueville H. & Renard J.L. (1988) Oil palm wilt in replantings: study methods and determination of certain environmental factors on the expression of this disease. *Oléagineux*, **43**, 149–157 [12.1.6.2]
- de Franqueville H. & Renard J.L. (1990) Improvement of oil palm vascular wilt tolerance. Results and development of the disease at the R. Michaux plantation. *Oléagineux*, **45**, 399–405 [5.5.2.3]
- de Franqueville H., Renard J.L., Philippe R. & Mariau D. (1991) Oil palm blast: prospects for improvement of the control method. *Oléagineux*, **46**, 223–231 [12.1.4]
- de Franqueville H., Diabate S. & Renard J.L. (1995) Study of oil palm clones performance with respect to vascular wilt caused by *Fusarium oxysporum* f.sp. *elaeidis* – results in early tests and replantings. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 684–688, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.4.3.1; 12.1.6.2]
- de Franqueville H., Asmady H., Jacquemard J.C., Hayun Z. & Durand-Gasselin T. (2001) Indications on sources of oil palm (*Elaeis guineensis* Jacq.) genetic resistance and susceptibility to *Ganoderma* sp., the cause of basal stem rot. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, p. 420–431, Malaysian Palm Oil Board, Kuala Lumpur [5.3.5; 12.1.6.3]
- de Graaf J. (1976) Composition, quality and end uses of palm oil. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 493–503, Elsevier, Amsterdam [13.4.6.1; 13.4.6.3; 14.3.3.3]
- Dekester A. (1962) La mise en place des jeunes palmiers à huile. *Oléagineux*, **17**, 475–482 [9.1.4.1]
- Delvare G. & Genty P. (1992) Intérêt des plantes attractives pour la faune auxiliaire dans les palmeraies d'Amérique tropicale. *Oléagineux*, **47**, 551–559 [12.2.1.1]
- Dent D. (1992) Reclamation of acid sulphate soils. *Adv. Soil Sci.*, **17**, 79–122 [11.8.1]
- Department of Agriculture. (1999) Land conservation act. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 271–272, Malaysian Oil Palm Growers' Council, Kuala Lumpur [8.1.5.4]
- de Poerck R. (1942) Comment expliquer les disjonctions anormales de certains *tenera*? *Bull. agric. Congo Belge*, **33**, 206–216 [5.3.3.1]
- Desassis A. (1955) La détermination de la teneur en huile de la pulpe de fruit d'*Elaeis guineensis*. *Oléagineux*, **10**, 823–827 [5.2.4.2]
- Desassis A. (1957) L'acidification de l'huile de palme. *Oléagineux*, **12**, 525–534 [13.3.3]
- Desmarest J. (1967) Essai d'irrigation sur jeune palmeraie industrielle. *Oléagineux*, **22**, 441–447 [4.1.4.2; 4.3.3.3; 4.4.5.1; 10.3]
- Desmier de Chenon R. (1979) Mise en évidence du rôle de *Recilia mica* Kramer (Homoptera, Cicadellidae, Deltocephalinae) dans la maladie du blast des pépinières de palmiers à huile en Côte d'Ivoire. *Oléagineux*, **34**, 107–113 [12.1.4]
- Desmier de Chenon R. (1984) Research on the genus *Lincus* Stal., Hemiptera Pentatomidae Discocephalinae, and its possible role in the transmission of the marchitez of oil palm and hart-rot of coconut. *Oléagineux*, **39**, 1–6 [12.1.6.4]
- Desmier de Chenon R., Mariau D., Monsarrat P., Fediere G. & Sipayung A. (1988) Research into entomopathogenic agents of viral origin in leaf-eating Lepidoptera of the oil palm and coconut. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 471–479, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.1.4]
- Desmier de Chenon R., Sipayung A. & Sinuraya L. (1996) Sex pheromone traps for monitoring the Limacodid populations of *Setothosea asigna* in Indonesian oil palm plantations. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 528–537, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.5.1]
- Desmier de Chenon R., Ginting C.U., Asmady, Sudharto P. & Sipayung A. (1998) Importance of the rhinoceros beetles in mature oil palm plantations for effective biocontrol. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 630–637, Indonesian Oil Palm Res. Inst., Medan, Indonesia [12.2.4.1]
- Desneux R. (1957) Prospection des palmeraies et sélection du palmier à huile au Kwango. *Bull. Inf. Inst. Nat. Etude Agron. Congo Belge*, **6**, 351–364 [5.1.7.1]
- Desneux R. (1958) Un palmier '*Pisifera*' remarquable. *Bull. Inf. Inst. Nat. Etude Agron. Congo Belge*, **7**, 95–104 [5.4.2.3]
- De Souza J. (2000) Mechanisation – its impact on productivity levels in the oil palm industry. *Planter, Kuala Lumpur*, **76**, 471–479 [10.2; 10.4.6]
- de Taffin G. & Daniel C. (1976) Premiers résultats d'un essai d'irrigation lente sur palmier à huile. *Oléagineux*, **31**, 413–419 [10.3]
- de Touchet B., Duval Y. & Pannetier C. (1990) *Oil palm (Elaeis guineensis Jacq.) regeneration from embryogenic suspension culture*. Paper presented at Int. Assoc. Plant Tissue Culture Congress, June 1990, Amsterdam [6.5.1.1]
- Devreux M. & Malingraux C. (1960) Pollen d'*Elaeis guineensis* Jacq. Recherches sur les méthodes de conservation. *Bull. agric. Congo Belge*, **5**, 543–566 [5.2.1.2]
- Devuyst A. (1948) Influence des pluies sur les rendements du palmier à huile. *Oléagineux*, **3**, 137–144 [4.5.4]
- Devuyst A.G. (1954) Selection of the oil palm (*Elaeis guineensis*) in Africa. *Trop. Agric., Trinidad*, **31**, 133–148 [5.2.7]
- de Wit C.T. (1965) *Photosynthesis of leaf canopies*, Centre for Agric. Publications and Documentation, Wageningen [4.1.4.2]
- Dhileepan K. (1988) Incidence and intensity of rhinoceros beetle infestation in oil palm plantations in India. *J. Plantation Crops*, **16**, 126–129 [12.2.4.1]
- Dhileepan K. (1990) Trials on the protection of oil palm fruit bunches from bird damage in India. *Planter, Kuala Lumpur*, **66**, 171–177 [12.3.3]
- Diabate S., Ledeme P., de Franqueville H. & Kouame B. (1992) Effet d'une souche avirulente de *Fusarium oxysporum* sur l'expression de la fusariose et sur les propriétés fungitoxiques des extraits racinaires de palmier à huile. In: *Proc. conf. 17–22 Feb., Dakar, Senegal. Interactions plantes-microorganismes*, pp. 307–320 [12.1.6.2]
- Dike K.O. (1956) *Trade and politics in the Niger Delta, 1830–85*, Oxford University Press, Oxford [1.2.3]
- Din M.A. & Rajanaidu N. (2000) *Evaluation of Elaeis oleifera, interspecific hybrids and backcrosses*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.1.7.3; 5.5.1.6]
- Djegui N., Adje A.I. & Daniel C. (1989) *Water consumption reduction in relation with planting densities*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [4.3.3]

- Dollet M. (1982) Les maladies des palmiers et cocotiers à protozoaires flagellés intraphloémiques en Amérique latine (*Phytomonas* sp., Trypanosomatidae). *Oléagineux*, 37, 9–12 [12.1.6.4]
- Dollet M. & Lopez G. (1978) Étude sur l'association de protozoaires flagellés à la Marchitez sorpresiva du palmier à huile en Amérique du Sud. *Oléagineux*, 33, 209–217 [12.1.6.4]
- Dollet M., Giannotti J. & Ollagnier M. (1977) Observations de protozoaires flagellés dans les tubes criblés de palmiers à huiles malades. *C. R. Acad. Sci. Paris, Ser. D*, 284, 643–645 [12.1.6.4]
- Donald C.M. (1962) In search of yield. *J. Austr. Inst. agric. Sci.*, 28, 171–178 [4.1.4.4]
- Donough C.R. (1990) Some observations of abnormally flowering clones. *Int. Soc. Oil Palm Breeders Newslett.* 8 (2), 4–8 [6.3.1.1]
- Donough C.R. (2002) *Best management practices for oil palm nurseries: a review of current knowledge and avenues for further improvements*. Paper presented at Seminar 'Best plantation management practices in oil palm', Asgard Information Services, Subang Jaya, Malaysia, 17–18 Dec. [7.2.5]
- Donough C.R. & Kwan B. (1991) Oil palm planting density: results from trials in Sabah and the possible options. *Planter, Kuala Lumpur*, 67, 483–508 [9.3.3; 9.3.6.2]
- Donough C.R. & Law I.H. (1988) The effect of weevil pollination on yield and profitability at Pamol Plantations. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'*, (Ed. by A. Halim Hassan *et al.*), pp. 523–527, Palm Oil Res. Inst., Malaysia, Kuala Lumpur [4.4.7.1]
- Donough C.R. & Law I.H. (1995) Breeding and selection for seed production at Pamol Plantations Sdn Bhd and early performance of Pamol D × P. *Planter, Kuala Lumpur*, 71, 513–530 [5.2.5; 5.4.1.2]
- Donough C.R. & Lee C.H. (1995) Longer term results from clone trials at Pamol Plantations and Golden Hope Plantations. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 116–133, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.4.2; 6.4.3.1]
- Donough C.R., Ng M. & Lai C. (1992) *Pamol's approach to quality control in controlled pollination for D × P seed production*. Paper presented at Incorp. Soc. Planters Seminar 'Advances in cocoa and oil palm in meeting future challenges', 16–17 June, Lahad Datu, Sabah [5.2.1.2]
- Donough C.R., Corley R.H.V. & Law I.H. (1995) 'Non-shedding' mutants of the oil palm. *Int. Soc. Oil Palm Breeders Newslett.* 11(2), 10–11 [5.6]
- Donough C.R., Chew K.W. & Law I.H. (1996a) Effect of fruit set on OER and KER: results from studies at Pamol Estates (Sabah) Sdn Bhd. *Planter, Kuala Lumpur*, 72, 203–219 [4.4.7.1; 4.5.2; 10.4.1]
- Donough C.R., Corley R.H.V., Law I.H. & Ng M. (1996b) First results from an oil palm clone × fertiliser trial. *Planter, Kuala Lumpur*, 72, 69–87 [5.5.1.7; 6.4.3.3]
- Doos B.R. (2000) Increasing food production at the expense of tropical forests. *Integrated Assessment*, 1, 189–202 [8.3.1]
- Dossa C. & Boisson C. (1991) *Compatibilité végétative chez des isolats du Fusarium oxysporum f.sp. elaeidis de différentes origines géographique*. Paper presented at Conference on *Fusarium* wilt of oil palm, Oct., Montpellier [7.1.5; 12.1.6.2]
- Dubos B. (1988) Regulation and maintenance of the water table in oil palm zones in Côte d'Ivoire. *Oléagineux*, 43, 201–206 [8.3.1]
- Dubos B., Caliman J.P., Corrado F., Quencez P., Suyanto S. & Tailliez B. (1999) Importance of magnesium nutrition in oil palm – results of several years' experiments. *Plantations, Recherche, Développement*, 6, 313–325 [8.1.3.6; 11.4.1.3; 11.5.1; 11.6.3; 11.9.2.5]
- Duckett J.E. (1982) Barn owls (*Tyto alba*) – a proven natural predator of rats in oil palm. In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 461–474, Incorp. Soc. Planters, Kuala Lumpur [12.3.1]
- Duckett J.E. (1999) *A guide to oil palm nurseries*. 3rd edn, Incorp. Soc. Planters, Kuala Lumpur [7.2]
- Duckett J.E. & Karupiah S. (1990) A guide to the planter in utilising barn owls (*Tyto alba*) as an effective biological control of rats in mature oil palm plantations. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 357–372, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.3.1]
- Duff A.D.S. (1963) The bud rot little leaf disease of the oil palm. *J. W. Afr. Inst. Oil Palm Res.*, 4, 176–190 [12.1.7.1]
- Duff A.D.S. (1970) *Cercospora elaeidis* Stey., and the oil palm. *Oléagineux*, 25, 329–332 [5.3.5; 12.1.2.1]
- Dufour O., Frere J.L., Caliman J.P. & Hornus P. (1988) Description of a simplified method of production forecasting in oil palm plantations based on climatology. *Oléagineux*, 43, 271–282 [3.2.3; 4.5.3; 4.5.4; 8.1.5.2]
- Dufrane M. & Berger J.L. (1957) Étude sur la récolte des palmeraies. *Bull. agric. Congo Belge*, 48, 581–640 [10.4.4.2]
- Dufrene E. (1989) *Photosynthèse, consommation en eau et modélisation de la production chez le palmier à huile (Elaeis guineensis Jacq.)*. Thesis, Univ. of Paris-Sud, Orsay [4.1.2; 4.1.4.3; 4.2.1.4; 11.2.1.4]
- Dufrene E. & Saugier B. (1989) Field studies of leaf gas exchanges in oil palm tree (*Elaeis guineensis* Jacq.). *Ann. Sci. Forest.*, 46 Suppl., 439s–442s [4.3.6.2]
- Dufrene E. & Saugier B. (1993) Gas exchange of oil palm in relation to light, vapour pressure deficit, temperature and leaf age. *Funct. Ecol.*, 7, 97–104 [4.1.4.3; 4.3.3.2; 4.3.4; 4.3.6.2]
- Dufrene E., Ochs R. & Saugier B. (1990) Oil palm photosynthesis and productivity linked to climatic factors. *Oléagineux*, 45, 345–355 [3.3.1; 4.1.4.3; 4.5.5]
- Dufty A.C., Senanayake F.R., Jack J.B. & Melvani K. (2000) Analogue forestry – a total ecosystem management approach that maximises biodiversity within plantation agriculture. *Planter, Kuala Lumpur*, 76, 671–696 [8.2.1]
- Dumet D., Engelmann F., Chabrilange N., Richaud F., Beule T., Durand-Gasselin T. & Duval Y. (1993a) Development of cryopreservation for oil palm somatic embryos using an improved process. *Oléagineux*, 48, 274 [6.2.2.1]
- Dumet D., Engelmann F., Chabrilange N., Duval Y. & Dereudde J. (1993b) Importance of sucrose for the acquisition of tolerance to desiccation and cryopreservation of oil palm somatic embryos. *Cryo-Letters*, 14, 243–250 [6.2.2.1]
- Dumet D., Engelmann F., Chabrilange N. & Duval Y. (1994a) Effect of desiccation and storage temperature on the conservation of cultures of oil palm somatic embryos. *Cryo-Letters*, 15, 85–90 [6.2.2.1]
- Dumet D., Engelmann F., Chabrilange N., Dussert S. & Duval Y. (1994b) Effect of various sugars and polyols on the tolerance to desiccation and freezing of oil palm polyembryonic cultures. *Seed Sci. Res.*, 4, 307–313 [6.2.2.1]
- Dumortier F. (1998) *Environmental and genetic aspects of oil palm precocity*. Paper presented at Int. Conf. 'Developments in oil palm industry for the 21st century', 21 Sept., Bali [12.1.5.1]

- Dumortier F. (1999) Performance and variability of oil palm $D \times P$ material in Papua New Guinea. In: *Proc. Seminar 'Performance of $D \times P$ planting material, clones and interspecific hybrids'* (Baranquilla, Colombia, June 1995) (Ed. by N. Rajanaidu & B.S. Jalani), pp. 58–75, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.5.2; 5.6]
- Dumortier F. (2000) *Utilisation of oil palm genetic resources at Dami Oil Palm Research Station*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.1.6.2; 5.2.3; 5.2.4.2; 5.2.6.2; 5.3.2; 5.3.3.2; 5.3.4.2]
- Dumortier F. & Konimor J. (1999) Selection and breeding progress in planting material at Dami OPRS, Papua New Guinea. In: *Proc. 1996 Seminar 'Sourcing of oil palm planting materials for local and overseas joint ventures'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 143–170, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.2; 5.3.4.1; 5.4.2.3; 5.6; 12.1.5.1]
- Dumortier F., van Amstel H. & Corley R.H.V. (1992) *Oil palm breeding at Binga, Zaire, 1970–1990*, Unilever Plantations, London [5.1.6.1; 5.2.4.2; 5.3.3.2; 5.4.2.4; 5.4.3; 5.5.1.4; 9.3.6.1; 12.1.6.2]
- Dunbabin V.M., Diggle A.J. & Rengel Z. (2002) Simulation of field data by a basic three-dimensional model of interactive root growth. *Plant Soil*, **239**, 39–54 [11.2.1.2]
- Dupriez G. (1956) Prépépinières d'*Elaeis*. *Bull. Inf. Inst. Nat. Etude Agron. Congo Belge*, **5**, 141–153 [7.2.1.2]
- Duran N., Salas R., Chinchilla C. & Peralta F. (1999) Manejo de la nutrición y fertilización en palma aceitera en Costa Rica. In: *Congreso nacional de suelos*, Vol. III, pp. 305–316 [1.4.3.10]
- Durand-Gasselin T., Duval Y., Baudouin L., Maheran A.B., Konan K. & Noiret J.M. (1995) Description and degree of the mantled flowering abnormality in oil palm (*Elaeis guineensis* Jacq.) clones produced using the Orstom-CIRAD procedure. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 48–63, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.1.1]
- Durand-Gasselin T., Noiret J.M., Kouamé K.R., Cochard B. & Adon B. (1999a) Availability of quality pollen for improved oil palm (*Elaeis guineensis* Jacq.) seed production. *Plantations, Recherche, Développement*, **6**, 264–276 [4.4.4.3; 5.4.2.3]
- Durand-Gasselin T., Baudouin L., Cochard B., Adon B. & Cao T.V. (1999b) Oil palm genetic improvement strategies. *Plantations, Recherche, Développement*, **6**, 344–360 [5.4.2.1; 5.4.2.2]
- Durand-Gasselin T., Konan K.E., Baudouin L. & Noiret J.M. (1999c) Performance of oil palm clones. In: *Proc. Seminar 'Worldwide performance of $D \times P$ oil palm planting materials, clones and interspecific hybrids'* (Baranquilla, Colombia, June 1995) (Ed. by N. Rajanaidu & B.S. Jalani), pp. 151–170, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.5; 6.3.1.2; 6.4.3.1]
- Durand-Gasselin T., Kouame K.R., Cochard B., Adon B. & Amblard P. (2000a) Diffusion variétale du palmier à huile (*Elaeis guineensis* Jacq.). *Ol Corps Gras Lipides*, **7**, 203–206 [5.1.6.1; 5.4.2.1; 5.4.2.2; 5.5.1.3; 5.5.2.3]
- Durand-Gasselin T., de Franqueville H., Diabate S., Cochard B. & Adon B. (2000b) *Assessing and utilizing sources of resistance to Fusarium wilt in oil palm (Elaeis guineensis Jacq.) genetic resources*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.5.2.3]
- Durand-Gasselin T., Cochard B., de Franqueville H., Nouy B., Potier F., Louise C., Amblard P. & Flori A. (2002) *Merits of a pedigree selection cycle for the creation of elite oil palm (E. guineensis Jacq.)*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst, Bali, 8–12 July. [5.4.2.2]
- Duval Y., Durand-Gasselin T., Konan K. & Pannetier C. (1988) *In vitro* vegetative micropropagation of oil palm (*Elaeis guineensis* Jacq.): strategy and results. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 191–196, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.2.1.1; 6.3.1.2]
- Duval Y., Engelmann F. & Durand-Gasselin T. (1995a) Somatic embryogenesis in oil palm (*Elaeis guineensis* Jacq.). In: *Somatic embryogenesis and synthetic seed* (Ed. by Y.P.S. Bajaj), pp. 335–352, Springer, Berlin [6.2.1]
- Duval Y., Aberlenc F. & de Touchet B. (1995b) Use of embryogenic suspensions for oil palm micropropagation. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 38–47, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.5.1.1]
- Duval Y., Bessi L., Verdeil J.L. & Maldiney R. (1995c) Study on the induction of the floral morphogenesis abnormality in oil palm during the *in vitro* regeneration process. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 64–76, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.2.1.1]
- Duval Y., Amblard P., Rival A., Konan E., Gogor S. & Durand-Gasselin T. (1997) Progress in oil palm tissue culture and clonal performance in Indonesia and the Côte d'Ivoire. In: *Plantation management for the 21st century* (Ed. by E. Pushparajah), pp. 291–307, Incorp. Soc. Planters, Kuala Lumpur [6.3.1.1; 6.4.2]
- Dyson T. (1999) World food demand and supply prospects in 2025. *J. R. Agric. Soc. Eng.*, **160**, 227–243 [1.4.2.2]
- Dzido J.L., Genty P. & Ollagnier M. (1978) Les principales maladies du palmier à huile en Equateur. *Oléagineux*, **33**, 55–63 [12.1.5.4; 12.1.6.4; 12.1.7.2]
- Eckersten H. (1994) Modelling daily growth and nitrogen turnover for a short rotation forest over several years. *Forest Ecol. Manage.*, **69**, 57–72 [11.6.1.5]
- Eeuwens C.J. (1976) Mineral requirements for growth and callus induction of tissue explants excised from mature coconut palms (*Cocos nucifera*) and cultured *in vitro*. *Physiol. Pl.*, **34**, 23–28 [6.2.1]
- Eeuwens C.J., Lord S., Donough C.R., Rao V., Vallejo G. & Nelson S. (2002) Effects of tissue culture conditions during embryoid multiplication on the incidence of 'mantled' flowering in clonally propagated oil palm. *Pl. Cell Tissue Organ Culture*, **70**, 311–323 [6.3.1.2; 6.3.3]
- Ejemba M.I. (1989) *Oil palm development in Nigeria: past efforts and future prospects*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov, Nigerian Inst. Oil Palm Res., Benin City [1.4.3.4]
- Ekanade O. (1998) An edaphic evaluation of a mixed cropping system based on cocoa grown in combination with oil palm in southwestern Nigeria. *Biol. Agric. Hort.*, **16**, 117–128 [8.4.3.3]
- Elena H., Schwartz D. & Vincens A. (1994) Pollen evidence of late Quaternary vegetation and inferred climatic change in the Congo. *Palaeogeography, Paleoclimatology, Palaeoecology*, **109**, 345–356 [1.1.1]
- Ellis R.H., Hong T.D., Roberts E.H. & Soetisna U. (1991) Seed

- storage behaviour in *Elaeis guineensis*. *Seed Sci. Res.*, **1**, 99–104 [7.1.3.2]
- Embrechts J., Poeloengan Z. & Sys K. (1988) Physical land evaluation using a parametric method. Application to oil palms in N. Sumatra. *Soil Surv. Land Eval.*, **8**, 111–112 [8.1.5.3]
- Engelmann F. (1990) Utilisation d'atmosphères à teneur en oxygène réduite pour la conservation de cultures d'embryons somatiques de palmier à huile (*Elaeis guineensis* Jacq.). *C. R. Acad. Sci. Ser. III*, **310**, 679–684 [6.2.2.2]
- Engelmann F. & Duval Y. (1986) Cryopreservation of oil palm somatic embryos (*Elaeis guineensis* Jacq.): results and application prospects. *Oléagineux*, **41**, 169–174 [6.2.2.1]
- Enig M.G. (1998) Palm oil and the anti-tropical campaign: good news towards counteracting a decade's worth of damage. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 115–126, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.6.4; 14.4]
- Enwezor W.O., Udo E.J. & Sobulo. (1981) Fertility status and productivity of acid sands. In: *'Acid Sands of Southern Nigeria', Monograph No. 1*, pp. 56–73, Soil Sci. Soc. Nigeria [3.5.2.2]
- Ergo A.B. (1997) New evidence for the African origin of *Elaeis guineensis* Jacq. by the discovery of fossil seeds in Uganda. *Ann. Gembloux*, **102**, 191–201 [1.1.1]
- Erhabor J.O. & Filson G.C. (1999) Soil fertility changes under an oil palm-based intercropping system. *J. Sustainable Agr.*, **14**, 45–61 [8.4.3.1]
- Ericsson T. (1999) The effect of pedigree error by misidentification of individual trees on genetic evaluation of a full-sib experiment. *Silvae Genetica*, **48**, 239–242 [5.2.6.2]
- Escobar R. (1980) An improved oil palm fruit depulper for single bunch lots. *Planter, Kuala Lumpur*, **56**, 540–542 [7.1.3.1]
- Escobar R. (1982) Preliminary results of the collection and evaluation of the American oil palm *Elaeis oleifera* (HBK, Cortes) in Costa Rica. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 79–93, Incomp. Soc. Planters, Kuala Lumpur [5.1.7.3]
- Escobar R., Sterling F. & Peralta F. (1999) Oil palm planting materials by ASD de Costa Rica. In: *Proc. 1996 Seminar 'Sourcing of oil palm planting materials for local and overseas joint ventures'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 171–187, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.3]
- Eswaran H., de Coninck F. & Varghese T. (1987) Role of plinthite and related forms of soil degradation. *Adv. Soil Sci.*, **11**, 109–128 [3.4.3.5]
- Evans L.T. (1993) *Crop evolution, adaptation and yield*, Cambridge University Press, Cambridge [4.1.1.2; 4.1.4.3; 4.2.2.1]
- Evans L.T. & Fischer R.A. (1999) Yield potential: its definition, measurement, and significance. *Crop Sci.*, **39**, 1544–1551 [10.7.1]
- Everaerts P.J. & Lubis B. (1976) Extraction of palm oil with a solvent. *Oléagineux*, **31**, 129–130 [13.4.3.5]
- Fadli M.L., Poeloengan Z. & Sisworo E.S. (2002) *P-fertiliser placement effectivity and determination of P-fertiliser efficiency on mature oil palm using 32P*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [11.2.1.3]
- Fairhurst T.H. (1998) *The oil palm – leaf sampling*. Potash & Phosphate Inst., Singapore [11.4.3; 11.4.4]
- Fairhurst T.H. (1999) Nutrient use efficiency in oil palm: measurement and management. *Planter, Kuala Lumpur*, **75**, 177–173 [11.6.1.3]
- Fairhurst T.H. & Mutert E. (1997) The industrial use of oil palm fibre: possible effects on plant nutrient cycles and sustainability. In: *Plantation management for the 21st century* (Ed. by E. Pushparajah), pp. 209–230, Incomp. Soc. Planters, Kuala Lumpur [13.6.1]
- Fairhurst T.H., Mutert E. & von Uexkull H.R. (1998) Agronomic management of oil palms on deep peat. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 226–239, Indonesian Oil Palm Res. Inst., Medan, Indonesia [3.4.3.7]
- Fairhurst T.H., Kerstan A.G., Rankine I.R. & Kuruvilla K.J. (2000) Use of geographic information systems in plantation agriculture: linking digital maps to agronomic database sets. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 755–767, Incomp. Soc. Planters, Kuala Lumpur [10.7.5]
- Falconer D.S. (1981) *Introduction to quantitative genetics*, 2nd edn, Longman, London [5.2.6; 5.4.1; 5.5.2.1]
- Fallavier P. & Olivin J. (1988) Experimental study of potassium and magnesium dynamics in a few tropical soils representative of oil palm growing zones. *Oléagineux*, **43**, 93–105 [11.6.1.2; 11.9.2.4]
- Fallavier P., Breyse M. & Olivin J. (1989) Experimental study of potassium dynamics in two tropical soils used for oil palm growing. *Oléagineux*, **44**, 197–207 [11.4.4.1; 11.6.1.2]
- FAO (2001) *Global forest resources assessment 2000*. Food and Agriculture Organisation, Rome [15.3.2]
- FAO–UNESCO (1990) *Soil map of the world 1:5000,000. Legend*, FAO, Paris [3.4.1.2; 3.4.3.9; 3.5.1.2; 3.5.2.1; 3.5.2.3]
- Farquhar J.H.J. (1913) *The oil palm and its varieties*, Crown Agents, for Govt of Nigeria, London [5.1.3.3]
- Fasoulas A. (1979) The honeycomb field designs. *Dept Genetics and Plant Breeding, Aristotelian Univ. Thessaloniki*, Publ. no. 9, 1–70 [5.2.2]
- Fatimah Arshad M. & Zainal Abidin M. (1993) Forecasting ability of Malaysian crude palm oil (CPO) futures price on physical price. In: *Proc. 1991 Int. Palm Oil Conf. – Promotion and marketing* (Ed. by Y. Basiron *et al.*), pp. 66–73, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.1.1]
- Fawzi A. (1994) Impact of light weight in-field vehicles on oil palm estates. In: *Management for enhanced profitability in plantations* (Ed. by Chee K.H.), pp. 299–305, Incomp. Soc. Planters, Kuala Lumpur [10.4.5]
- Fawzi H.A., Zainudin M.N. & Abdul Wahab A.A. (1998) Cattle integration in oil palm – establishment and financial implications. *Planter, Kuala Lumpur*, **74**, 319–334 [8.4.3.4]
- Fearnside P.M. (2001) Soybean cultivation as a threat to the environment in Brazil. *Environ. Conserv.*, **28**, 23–38 [14.2.2; 15.3.2]
- Fedepalma (2000) *Visión y estrategias de la palmicultura Colombiana: 2000–2020*. Fedepalma, Bogota [1.4.3.9; 14.2.1]
- Fediere G., Philippe R., Veyrues J.C. & Monsarrat P. (1990) Biological control of the oil palm pest *Latoia viridissima* (Lepidoptera, Limacodidae) in Côte d'Ivoire, by a new picornavirus. *Entomophaga*, **35**, 347–347 [12.2.5.1]
- Fenn L.B. & Hossner L.R. (1985) Ammonia volatilisation from ammonia or ammonium-forming nitrogen fertilisers. *Adv. Soil Sci.*, **1**, 124–170 [11.9.2.2]
- Ferrand M. (1960) Le noli (*Elaeis melanococca* ou *Corozo oleifera* en Colombia). *Oléagineux*, **15**, 823–827 [2.3.1]

- Ferwerda J.D. (1954) Boron deficiency on oil palms in the Kasai region of the Belgian Congo. *Nature*, **173**, 1097 [12.1.7.1]
- Ferwerda J.D. (1955) *Questions relevant to replanting in oil palm cultivation*. Thesis, Wageningen Univ., Wageningen [8.3.4.3]
- Ferwerda J.D. (1977) Oil palm. In: *Ecophysiology of tropical crops* (Ed. by P.deT. Alvim & T.T. Kozłowski), pp. 351–383, Academic Press, London [3.2.1]
- Fickendey E. (1944) Die Züchtung der Ölpalme (*Elaeis guineensis* Jacq.). *Z. Pflanzenzücht.*, **26**, 136–162 [5.3.4.4]
- Figueroa A. & van den Hove J. (1967) Contribución al estudio de la 'escoriación' de los frutos de la palmera de aceite en Colombia el *Himatidium neivai*. *Oléagineux*, **22**, 15–18 [12.2.8.3]
- Fleming T. (1969) Co-ordination of harvesting, transport and processing of oil palm crop. In: *Progress in oil palm* (Ed. by P.D. Turner), pp. 302–309, Incomp. Soc. Planters, Kuala Lumpur [4.5.1]
- Flood J., Cooper R.M. & Lees P.E. (1989) An investigation of pathogenicity of four isolates of *Fusarium oxysporum* from South America, Africa and Malaysia to clonal oil palm. *J. Phytopathol.*, **124**, 80–88 [12.1.6.2]
- Flood J., Mepsted R. & Cooper R.M. (1990) Contamination of oil palm pollen and seeds by *Fusarium* spp. *Mycol. Res.*, **94**, 708–709 [7.1.5; 12.1.6.2]
- Flood J., Mepsted R., Turner S. & Cooper R.M. (1994) Population dynamics of *Fusarium* species on oil palm seeds following chemical and heat treatments. *Pl. Pathol.*, **43**, 177–182 [7.1.5; 12.1.6.2; 12.1.10]
- Flood J., Meon S., Chung G.F., Leidi A. & Miller R.N.G. (1998) *Spatial mapping of Ganoderma in the field*. Paper presented at Int. Workshop on *Ganoderma* diseases, 5–8 Oct., Malay. Agric. Res. Dev. Inst., Serdang, Malaysia [12.1.6.3]
- Flood J., Bridge P.D. & Holderness M. (2000a) *Ganoderma diseases of perennial crops*, CABI Publishing, Wallingford [12.1.6.3]
- Flood J., Hasan Y., Turner P.D. & O'Grady E.B. (2000b) The spread of *Ganoderma* from infective sources in the field and its implication for management of the disease in oil palm. In: *Ganoderma diseases of perennial crops* (Ed. by J. Flood, P.D. Bridge & M. Holderness), pp. 101–112, CABI Publishing, Wallingford [12.1.6.3]
- Flowers T.J. (1988) Chloride as a nutrient and as an osmoticum. *Adv. Pl. Nutr.*, **3**, 55–78 [11.4.5.1]
- Fold N. (2000) Oiling the palms: restructuring of settlement schemes in Malaysia and the new international trade regulations. *World Development*, **Oxford**, **28**, 473–486 [1.5.3]
- Foong S.F. (1982) An improved weather-based model for estimating oil palm fruit yield. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 327–350, Incomp. Soc. Planters, Kuala Lumpur [4.5.3; 4.5.4]
- Foong S.F. (1993) Potential evapotranspiration, potential yield and leaching loss of oil palm. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 105–119, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.2.2.1; 3.2.3; 11.6.2.6; 11.7.4.1]
- Foong S.F. (1999) Impact of moisture on potential evapotranspiration, growth and yield of oil palm. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 64–86, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.2.2.1]
- Foong S.F. & Syed Sofi S.O. (1988) Two 4² NK factorial fertiliser trials on Rengam and Kuantan series soils in mature oil palm. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 329–332, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.3.1]
- Foong S.F. & Syed Sofi S.O. (1995) Frequency of CIRP application in oil palm. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 345–350, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.6.1.2; 11.9.2.3]
- Forde S.C.M. (1963) Soil chemistry division. In: *11th Annu Rep. W. Afr. Inst. Oil Palm Res.*, pp. 98–104, Benin City [11.2.1.2]
- Forde S.C.M. (1972) Effect of dry season on uptake of radioactive phosphorus by surface roots of the oil palm (*Elaeis guineensis* Jacq.). *Agron. J.*, **64**, 622–623 [4.2.1.4; 11.2.1.3]
- Foster H.L. (1995) Experience with fertiliser recommendation systems for oil palm. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 313–328, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.5.1.1; 11.4.4.1; 11.4.5.2; 11.6.4.1; 11.6.4.3; 11.6.4.4; 11.6.4.5]
- Foster H.L. (2002) Assessment of oil palm fertiliser requirements. In: *The oil palm – management for large and sustainable yields* (Ed. by T.H. Fairhurst & R. Härdter), Potash & Phosphate Institute of Canada (ESEAP), Singapore [10.5.2; 11.3.1; 11.3.3.2; 11.4.4.2; 11.4.4.3; 11.5.1; 11.6.1.2; 11.6.4]
- Foster H.L. & Chang K.C. (1977) The diagnosis of the nutrient status of oil palms in West Malaysia. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 290–312, Incomp. Soc. Planters, Kuala Lumpur [11.4.4.2; 11.5.1; 11.6.4.1; 11.6.4.4; 11.6.4.6; 11.9.1]
- Foster H.L. & Prabowo N.E. (1996a) *Yield response of oil palm to P fertilisers on different soils in North Sumatra*. Paper presented at Conf. 'Sustainability of oil palm plantations – agronomic and environmental perspectives', Int. Soc. Oil Palm Agronomists, Kuala Lumpur [11.3.3.1]
- Foster H.L. & Prabowo N.E. (1996b) Variation in the potassium fertiliser requirements of oil palm in North Sumatra. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 143–152, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.3.2.3; 11.3.3.1; 11.4.2.2; 11.8.2]
- Foster H.L. & Prabowo N.E. (2002) *Overcoming the limitations of foliar diagnosis in oil palm*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [11.4.2.2]
- Foster H.L. & Tarmizi Mohamad A. (1988) Variation in the fertilizer requirements of oil palm in Peninsular Malaysia. I. Within the same soil series. *Palm Oil Res. Inst. Malaysia, Bull.*, **16**, 1–9 [11.3.3.2; 11.6.4.1]
- Foster H.L., Ghazali M.Z. & Tayeb Dolmat M. (1984a) The available water holding capacity of oil palm soils in Malaysia. *Palm Oil Res. Inst. Malaysia, Bull.*, **8**, 1–9 [10.3.1.2]
- Foster H.L., Tarmizi Mohamad A., Tayeb Dolmat M., Chow C.S., Chang K.C. & Zin Z.Z. (1984b) The estimation of N and K fertilizer requirements of oil palm in Peninsular Malaysia. In: *Proc. Int. Conf. 'Soils and nutrition of perennial crops'*, pp. 349–365, Malaysian Soil Sci. Soc., Kuala Lumpur [11.3.3.1; 11.6.4.3]
- Foster H.L., Tayeb Dolmat M. & Zin Z.Z. (1985a) Oil palm yields in the absence of N and K fertilisers in different environments in Peninsular Malaysia. *Palm Oil Res. Inst. Malaysia, Occ. Paper*, **15**, 1–17 [11.5.1; 11.6.4.2; 11.6.4.3]
- Foster H.L., Chang K.C., Tayeb Dolmat M., Tarmizi Mohamad

- A. & Zin Z.Z. (1985b) Oil palm yield responses to N and K fertilisers in different environments in Peninsular Malaysia. *Palm Oil Res. Inst. Malaysia, Occ. Paper*, 16, 1–23 [11.3.1; 11.3.3.2; 11.6.4.3]
- Foster H.L., Tarmizi Mohamad A., Tayeb Dolmat M., Chang K.C., Zin Z.Z. & Halim Hassan A. (1986) Fertiliser recommendations for oil palm in Peninsular Malaysia. *PORIM Technol.*, 13, 1–25 [11.6.4.1; 11.6.4.2; 11.6.4.3]
- Foster H.L., Tarmizi Mohamad A., Tayeb Dolmat M. & Zin Z.Z. (1988a) Oil palm yield responses to P fertilisers in Peninsular Malaysia. *Palm Oil Res. Inst. Malaysia, Bull.*, 17, 1–8 [11.5.1; 11.6.4.5]
- Foster H.L., Tayeb Dolmat M. & Gurmit S. (1988b) The effect of fertilisers on oil palm bunch components in Peninsular Malaysia. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 294–304, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.5.2; 11.3.2.4; 11.4.4.1]
- Foster H.L., Tarmizi Mohamad A. & Zin Z.Z. (1988c) Foliar diagnosis of oil palm in Peninsular Malaysia. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 249–261, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.4.2.1; 11.4.4.1; 11.6.4.1; 11.6.4.5]
- Foster H.L., Wilkie A.S. & Orrell I. (1993) The effect of chloride fertilisers applied to oil palms on volcanic soils in Papua New Guinea. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 350–359, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.3.1; 11.4.5.1; 11.4.5.2; 11.8.2]
- Franke M., Berna J.L., Cavalli L., Renta C., Stalmans M. & Thomas H. (1995) A life-cycle inventory for the production of petrochemical intermediates in Europe. *Tenside Surf. Det.*, 32, 384–396 [14.3.6.1]
- Fraselle J.V. (1951) Experimental evidence of the pathogenicity of *Fusarium oxysporum* Schl. F. to the oil palm (*Elaeis guineensis* J.). *Nature*, 167, 447 [12.1.6.2]
- Frazelle J. & Buyckx E.J.E. (1962) Maladies et animaux nuisibles du palmier à huile. *Pub. Inst. Nat. Etude agron. Congo Belge, Hors Ser.* 227–272 [12.2.5.3]
- Freeman W.G. (1925) Report of the Department of Agriculture, Trinidad and Tobago (Abstract). *Rev. appl. Entomol.*, 14, 546 [12.1.6.6]
- Fry J. (1996) Price trends in oilseeds, vegetable oils and meals and the cost-competitiveness of Asian producers. *Plantations, Recherche, Développement*, 3, 97–102 [14.2.2]
- Fry J. (1998) Implications of recent developments in Asian economies and in the global economy for the palm oil industry. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 28–36, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.4.2.1; 11.3.2.3; 14.1.3; 14.2.1]
- Fry J. (2002) *The competitive position of palm oil in the global oil market*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [1.4.2.4; 14.2.2]
- Galt R. (1953) Methods of germinating oil palm seeds. *J. W. Afr. Inst. Oil Palm Res.*, 1, 74–87 [7.1.4.3]
- Gan L.T. & Ho C.Y. (1994) Impact of rising labour cost on choice of plantation crops for the estate sector. In: *Management for enhanced profitability in plantations* (Ed. by Chee K.H.), pp. 499–511, Incorp. Soc. Planters, Kuala Lumpur [1.4.2.4; 14.2.2]
- Gan L.T., Ho C.Y., Chew J.S., Lam K.S. & Kee T.T. (1994) Recent developments in harvesting practices to maximise labour productivity, oil yields and profits. In: *Management for enhanced profitability in plantations* (Ed. by Chee K.H.), pp. 315–336, Incorp. Soc. Planters, Kuala Lumpur [10.4.4]
- Gan L.T., Ho C.Y., Lam K.S. & Chew J.S. (1995) Optimum harvesting standards to maximise labour productivity and oil recovery. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 195–211, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.5.2; 10.4.4; 10.4.7]
- Gapor Mohd Top A. (1990) Effect of refining and fractionation on vitamin E in palm oil. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Chemistry, technology and marketing*, pp. 261–265, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.4.3]
- Garcia J.A., Belalcazar R., Galvis N. & Gomez P.L. (1998) Palm oil extraction rate variation in Colombia (specific cases). In: *Proc. 1996 Int. Conf. 'Oil and kernel production in oil palm – a global perspective'* (Ed. by N. Rajanaidu, I.E. Henson & B.S. Jalani), pp. 317–329, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.5.2]
- Gascon J.P. & de Berchoux C. (1963) Caractéristiques qualitatives du régime d'*Elaeis guineensis* Jacq. Quelques relations entre les *dura* et *tenera* d'une même descendance et leur application à l'amélioration des semences. *Oléagineux*, 18, 411–416 [5.3.3.1; 5.3.3.2]
- Gascon J.P. & de Berchoux C. (1964) Caractéristiques de la production d'*Elaeis guineensis* (Jacq.) de diverses origines et leurs croisements. Application à la sélection du palmier à huile. *Oléagineux*, 19, 75–84 [5.1.3.1; 5.1.6.1; 5.3.2; 5.4.2.1; 5.4.3]
- Gascon J.P. & Meunier J. (1979) Anomalies d'origine génétique chez le palmier à huile *Elaeis*. Description et résultats. *Oléagineux*, 34, 437–447 [12.1.5.3]
- Gascon J.P. & Wuidart W. (1975) Amélioration de la production et de la qualité de l'huile d'*Elaeis guineensis* Jacq. *Oléagineux*, 30, 1–4 [5.3.7.2]
- Gascon J.P., Noiret J.M. & Benard G. (1966) Contribution à l'étude de l'hérédité de la production de régimes d'*Elaeis guineensis* Jacq. Application à la sélection du palmier à huile. *Oléagineux*, 21, 657–661 [5.4.2.1; 5.4.3]
- Gascon J.P., Noiret J.M. & Meunier J. (1969) Effets de la consanguinité chez *Elaeis guineensis* Jacq. *Oléagineux*, 24, 603–611 [5.4.3]
- Gascon J.P., Jacquemard J.C., Houssou M., Boutin D., Chaillard H. & Kanga-Fondjo F. (1981) La production de semences sélectionnées de palmier à huile *Elaeis guineensis*. *Oléagineux*, 36, 476–486 [5.1.6.1; 5.5.2.3]
- Gascon J.P., Le Guen V., Nouy B., Asmady & Kanga F. (1988) Results of second cycle recurrent reciprocal selection trials on oil palm. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 112–117, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.2.3; 6.4.2]
- Gaspar T., Smith D. & Thorpe T. (1977) Arguments supplémentaires en faveur d'une variation inverse du niveau auxinique endogène au cours des deux premières phases de la rhizogénèse. *C. R. Acad. Sci., Paris*, 285, 327–330 [6.2.3]
- Genty P. (1968) Deux lépidoptères nuisibles au palmier à huile. *Oléagineux*, 23, 645–648 [12.2.5.3]
- Genty P. (1973) Observations préliminaires du lépidoptère mineur des racines du palmier à huile, *Sagalassa valida*, Walker. *Oléagineux*, 28, 59–65 [12.1.6.4; 12.2.7.1]
- Genty P. (1976) Etude morphologique et biologique d'un lépi-

- doptère défoliateur du palmier à huile en Amérique latine *Darna metaleuca* Walker. *Oléagineux*, 31, 99–104 [12.2.5.1]
- Genty P. (1977) Les ravageurs et les maladies du palmier à huile et du cocotier. Les lépidoptères mineurs de racines: *Sagalassa valida* W. *Oléagineux*, 32, 311–314 [12.1.6.4; 12.2.7.1]
- Genty P. (1978) Morphologie et biologie d'un lépidoptère défoliateur du palmier à huile en Amérique latine, *Stenoma cecropia* Meyrick. *Oléagineux*, 33, 421–427 [12.2.5.2]
- Genty P. (1981) Recherche entomologique sur le palmier à huile en Amérique latine. *Oléagineux*, 36, 585–594 [12.1.6.4; 12.2.5.1; 12.2.7.1]
- Genty P. & Celis L.A. (1997) *Preliminary study in the behaviour of the inter-specific hybrid between E. guineensis and E. oleifera (Brazil)*. Paper presented at Int. Soc. Oil Palm Agronomists Workshop, 2 Sept., Cartagena, Colombia [2.4; 5.5.1.6]
- Genty P. & Mariau D. (1973) Les ravageurs et maladies du palmier à huile et du cocotier. Le genre *Himatidium*. *Oléagineux*, 28, 513–515 [12.2.8.3]
- Genty P. & Mariau D. (1975) Morphologie et biologie du Pyralidae des racines de l'*Elaeis*, *Sufetula diminutalis*. *Oléagineux*, 30, 147–152 [12.2]
- Genty P. & Reyes E. (1977) Un nouvel acararien du palmier à huile: l'Eriophyidae 'Retracrus elaeis Keifer.' *Oléagineux*, 32, 255–262 [12.2]
- Genty P., Gildardo Lopez J. & Mariau D. (1975) Dégâts de *Pestalotiopsis* induits par des attaques de *Gargaphia* en Colombie. *Oléagineux*, 30, 199–204 [12.1.5.2]
- Genty P., Desmier de Chenon R. & Morin J.P. (1978) Les ravageurs du palmier à huile en Amérique latine. *Oléagineux*, 33, 325–419 [12.2; 12.2.5.1; 12.2.5.2]
- Genty P., Garzon M.A. & Garcia R. (1983) Dégâts et contrôle du complexe *Leptopharsa-Pestalotiopsis* chez le palmier à huile. *Oléagineux*, 38, 291–299 [12.1.5.2]
- George S.T., Chung G.F. & Zakaria K. (1996) Updated results (1990–1995) on trunk injection of fungicides for the control of *Ganoderma* basal stem rot. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin et al.), pp. 508–515, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.3]
- Gerber K. & Giblin-Davis R.M. (1990) Association of the red-ring nematode and other nematode species with the palm weevil, *Rhynchophorus palmarum*. *J. Nematol.*, 22, 143–149 [12.1.6.6]
- Gerritsma W. (1988) *Light interception, leaf photosynthesis and sink-source relations in oil palm*. Wageningen Agricultural University, The Netherlands [4.1.4.3; 4.2.2.1; 4.3.2.2; 4.3.8]
- Gerritsma W. & Soebagyo F.X. (1999) An analysis of the growth of leaf area of oil palms in Indonesia. *Expl Agric.*, 35, 293–308 [4.1.4.2; 4.2.1.1]
- Gerritsma W. & Wessel M. (1997) Oil palm: domestication achieved? *Neth. J. agric. Sci.*, 45, 463–475 [1.2.3; 1.3.2; 4.1.4.3]
- Ghesquiere M. (1984) Enzyme polymorphism in oil palm (*Elaeis guineensis* Jacq.) I. Genetic control of nine enzyme systems. *Oléagineux*, 39, 561–574 [5.2.8.1]
- Ghesquiere M. (1985) Enzyme polymorphism in oil palm (*Elaeis guineensis* Jacq.) II. Variability and genetic structure of seven origins of oil palm. *Oléagineux*, 40, 529–540 [5.2.8.1]
- Giardina C.P., Sanford R.L., Deckersmith I.C. & Jaramailla V.J. (2000) The effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. *Pl. Soil*, 220, 247–260 [8.3.2]
- Giblin-Davis R., Gerber K. & Griffith R. (1989) *In vivo* and *in vitro* culture of the red ring nematode, *Rhadinaphelenchus cocophilus*. *Nematropica*, 19, 135–142 [12.1.6.6]
- Giblin-Davis R.M., Oehlschlager A.C., Perez A., Gries G., Gries R., Weissling T.J., Chinchilla C.M., Pena J.E., Hallett R.H., Pierce H.D. & Gonzalez L.M. (1996) Chemical and behavioral ecology of palm weevils (Curculionidae: Rhynchophorinae). *Florida Entomologist*, 79, 153–167 [12.2.6.1]
- Gilbert A.C. (1979) Sprinkler irrigation and practice under Malaysian conditions. *Planter, Kuala Lumpur*, 55, 170–184 [7.2.2.3]
- Ginting C.U. & Desmier de Chenon R. (1987) Application of the systemic insecticide root absorption technique for the long-term protection of coconut palms and other commercial crops. *Oléagineux*, 42, 63–73 [12.2.1.4]
- Glantz M.H. (2001) *Currents of change: impacts of El Niño and La Niña on climate and society*. Cambridge University Press, Cambridge [3.3.2]
- Glenister A.G. (1951) *The birds of the Malay Peninsula, Singapore and Penang*. Paperback edn (1971), Oxford University Press, Kuala Lumpur [12.3.1]
- Gobin A.M., Campling P., Deckers J.A., Poesan J. & Feyen J. (1999) Soil erosion movement at the Udi-Nsukka Cuesta (south eastern Nigeria). *Land Degrad. Develop.*, 10, 141–160 [3.5.2.1; 8.1.3.2]
- Goh K.H. (1977) A systematic design for oil palm spacing trials. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 168–182, Incomp. Soc. Planters, Kuala Lumpur [9.3.3.1; 11.3.2.1]
- Goh K.H. (1982) Analyses of oil palm spacing experiments. In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 393–414, Incomp. Soc. Planters, Kuala Lumpur [9.3.3.1; 9.3.3.3; 11.9.1]
- Goh K.J. (2000) Climatic requirements of the oil palm for high yields. In: *Managing oil palm for high yields: agronomic principles* (Ed. by Goh K.J.), pp. 1–17, Malaysian Soc. Soil Sci. and Param Agric. Surveys, Kuala Lumpur [3.2.1; 3.2.3; 3.3.1; 8.1.5.4]
- Goh K.J. & Chew P.S. (2000) A lecture note on agronomic requirement of oil palm for high yields in Malaysia. In: *Managing oil palm for high yields: agronomic principles* (Ed. by Goh K.J.), pp. 39–97, Malaysian Soc. of Soil Sci. and Param Agric. Surveys, Kuala Lumpur [3.4.3.8; 8.2.3; 8.3.1; 8.3.2; 8.3.4.2; 8.4.2; 10.1.2.2]
- Goh K.J., Chew P.S. & Kee K.K. (1994a) *K nutrition for mature oil palm in Malaysia*, IPI Res. Topics 17, Int. Potash Inst., Basel [11.5.1; 11.7.1]
- Goh K.J., Chew P.S. & Teo C.B. (1994b) Commercial yield performances of oil palms in Sabah, Malaysia. *Planter, Kuala Lumpur*, 70, 497–507 [1.4.3.2; 10.7.1]
- Goh K.J., Chew P.S. & Teo C.B. (1994c) Maximising and maintaining oil palm yields on commercial scale in Malaysia. In: *Management for enhanced profitability in plantations* (Ed. by Chee K.H.), pp. 121–141, Incomp. Soc. Planters, Kuala Lumpur [8.1.5.1; 8.1.5.4; 8.1.6; 8.3.1; 10.7.1; 10.7.2; 10.7.3]
- Goh K.J., Chew P.S. & Gan H.H. (1997) Quantitative land evaluation for sustainability of oil palm plantations. In: *Plantation management for the 21st century* (Ed. by E. Pushparajah), pp. 311–322, Incomp. Soc. Planters, Kuala Lumpur [8.1.5.4]

- Goh K.J., Chew P.S. & Teoh K.C. (1998) Ground magnesium limestone as a source of magnesium for mature oil palm on sandy soil in Malaysia. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 347–362, Indonesian Oil Palm Res. Inst., Medan, Indonesia [11.6.2.5]
- Goh K.J., Teo C.B., Chew P.S. & Chiu S.R. (2000) Fertiliser management in oil palm – agronomic principles and field practices. In: *Managing oil palm for high yields: agronomic principles* (Ed. by Goh K.J.), pp. 98–122, Malaysian Soc. of Soil Sci. and Param Agric. Surveys, Kuala Lumpur [11.9.2.1]
- Goh S.H. (1998) Minor components in palm oil: nutritional attributes. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 459–467, Indonesian Oil Palm Res. Inst., Medan, Indonesia [13.1.3; 13.1.4; 13.1.4.1]
- Gomez P.L., Calvache H., Nieto L.E., Acosta A., Alvaril F. & Mora S. (1996) Pests and diseases of oil palm in South America: the South American experience. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 303–311, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.4.3.9; 12.1.6.4; 12.1.6.6]
- Gomez P.L., Ayala L. & Munevar F. (2000) Characteristics and management of bud rot, a disease of oil palm. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 545–553, Incomp. Soc. Planters, Kuala Lumpur [12.1.7.2]
- Gopinathan B. & Joseph K.T. (1980) Anomalies in the classification by the US Soil Taxonomy of alluvial soils with special reference to pyrite-containing alluvia. In: *Proc. Conf. Classification and management of tropical soils* (Ed. by K.T. Joseph), pp. 158–167, Malay. Soc. Soil Sci., Kuala Lumpur [3.5.1.1]
- Goudriaan J. & Monteith J.L. (1990) A mathematical function for crop growth based on light interception and leaf area expansion. *Ann. Bot.*, **66**, 695–701 [4.1.1.1]
- Graham J.W. & Soupa R. (2000) Mechanical in-field collection of FFB in New Britain Palm Oil Ltd's plantations in Papua New Guinea. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 673–685, Incomp. Soc. Planters, Kuala Lumpur [10.4.6]
- Gray B.S. (1966) The necessity for assisted pollination in areas of low male inflorescence production and its effect on the components of yield of the oil palm (*Elaeis guineensis*). *Planter, Kuala Lumpur*, **42**, 1–7 [4.4.7.1]
- Gray B.S. (1969) *A study of the influence of genetic, agronomic and environmental factors on the growth, flowering and bunch production of the oil palm on the west coast of West Malaysia*. Thesis, Univ. of Aberdeen, Aberdeen [4.1.3.3; 4.2.2.4; 4.4.5; 11.2.1.2]
- Gray B.S. & Hew C.K. (1963–1966) *Annual reports, Oil Palm Research Station, Banting, 1962, 1963, 1964 and 1965*. Harrisons and Crosfield (Malaysia) [9.1.1]
- Gray B.S. & Hew C.K. (1968) Cover crop experiments in oil palms on the west coast of Malaya. In: *Oil palm developments in Malaysia* (Ed. by P.D. Turner), pp. 56–65, Incomp. Soc. Planters, Kuala Lumpur [10.1.2.3]
- Gray B.S. & Siggs A.J. (1994) Global perspective of the future of the oil palm industry. In: *Management for enhanced profitability in plantations* (Ed. by Chee K.H.), pp. 1–20, Incomp. Soc. Planters, Kuala Lumpur [14.2.1]
- Green A.H. (1973) *Annual review of research, 1971*. Unilever Plantations Group, London [5.1.3.3]
- Gregory P.J., Ingram J.S.I., Campbell B., Goudriaan J., Hunt A., Landsberg J.J., Linder S., Stafford-Smith M., Sutherst R.W. & Valentin C. (1999) Managed production systems. In: *The terrestrial biosphere and global change* (Ed. by B. Walker *et al.*), pp. 227–270, Cambridge University Press, Cambridge [3.3.2]
- Gries G., Gries R., Perez A.L., Oehlschlager A.C., Gonzalez L.M., Pierce H.D., Kouda M., Zebeyou M. & Nanou N. (1993) Aggregation pheromone of the African palm weevil, *Rhynchophorus phoenicis* F. *Naturwissenschaften*, **80**, 90–91 [12.2.6.1]
- Gries G., Gries R., Perez A.L., Gonzalez L.M., Pierce H.D., Oehlschlager A.C., Rhainds M., Zebeyou M. & Kouame B. (1994) Ethyl propionate: synergistic kairomone for African palm weevil, *Rhynchophorus phoenicis* L. (Coleoptera: Curculionidae). *J. Chem. Ecol.*, **20**, 889–897 [12.2.6.1]
- Griffing B. (1963) Comparisons of potentials for general combining ability selection methods utilising one or two random mating populations. *Aust. J. biol. Sci.*, **16**, 838–862 [5.4.2.1]
- Griffiths W., Fairhurst T.H., Rankine I.R., Kerstan A.G. & Taylor C. (2002) *Identification and elimination of yield gaps in oil palm. Use of OMP7 and GIS*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [10.7.4]
- Grout B.W.W., Shelton K. & Pritchard H.W. (1983) Orthodox behaviour of oil palm seed and cryopreservation of the excised embryo for genetic conservation. *Ann. Bot.*, **52**, 381–384 [6.2.2.1]
- Guerra de la Espriella A. (1984) Palma africana: el nuevo cultivo Colombiano. *Palmas (Bogota)*, **5** (3), 9–12 [1.4.3.9]
- Guerrero A.V. (1985) Cria de *Chrysopa* spp. en laboratorio para control del chinche de encaje *Leptopharsa gibbicarina* (Froech). *Palmas (Bogota)*, **6**(3), 25–33 [12.1.5.2]
- Guerts T. (2000) Financing palm oil plantation projects in emerging countries. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 699–716, Incomp. Soc. Planters, Kuala Lumpur [1.4.3]
- Guldentops R.E. & Scuvie L. (1968) Recherche de la densité optimale pour le palmier à huile planté en allées. *Publ. Inst. Nat. Etude agron. Congo Belge, Ser. Tech. Sci.*, **75**, 1–72 [9.3.4; 9.3.6.3]
- Gunn J.S. (1962) The economics of manuring the oil palm. *J. W. Afr. Inst. Oil Palm Res.*, **3**, 302–307 [11.3.2.3]
- Gunn J.S. & Sheldrick R.D. (1963) The influence of the age and size of oil palm seedlings at the time of transplanting to the field on their subsequent growth. *J. W. Afr. Inst. Oil Palm Res.*, **4**, 191–200 [9.1.1]
- Gunn J.S. & Sly J.M.A. (1961) Agronomy Division. In: *9th Annu. Rep. W. Afr. Inst. Oil Palm Res.*, pp. 29–69, Benin City [7.2.2.3]
- Gunn J.S., Sly J.M.A. & Chapas L.C. (1961) The development of improved nursery practices for the oil palm in West Africa. *J. W. Afr. Inst. Oil Palm Res.*, **3**, 198–232 [7.2.1, 7.2.2.2, 7.2.4; 12.1.2.2]
- Gurmit S. (1988) Zinc nutrition of oil palms on peat soils. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 321–328, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.4.1.3; 11.8.4; 11.8.5]
- Gurmit S. (1990) Fertiliser responses in oil palms on a range of alluvial soils. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 383–394, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.3.2.3; 11.8.4]

- Gurmit S. (1991) *Ganoderma* – the scourge of oil palms in the coastal areas. *Planter, Kuala Lumpur*, **67**, 421–444 [12.1.6.3]
- Gurmit S. (1999) The Malaysian oil palm industry: progress towards environmentally sound and sustainable crop production. *Industry & Environment*, **22**, 45–48 [1.4.2.4; 1.5.4; 8.3.1]
- Gurmit S. & Toh T.S. (2000) Integrating the production of granulated organic fertilisers, compound animal feed and fibre in the palm oil mill. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 843–850, Incomp. Soc. Planters, Kuala Lumpur [13.4.8.2; 13.6.3]
- Gurmit S., Tan Y.P. & Ho C.Y. (1981) Mechanical systems of bunch mulching oil palms in the Lower Perak district. In: *Proc. Natn. Workshop 'Oil palm by-product utilisation'*, pp. 129–134, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [9.4.2]
- Gurmit S., Tan Y.P., Rajah Padman C.V. & Lee F.W. (1987) Experiences on the cultivation and management of oil palms on deep peat in United Plantations Berhad. *Planter, Kuala Lumpur*, **63**, 143–157 [3.4.3.7]
- Gurmit S., Lim K.C., Teo L. & Kow D.L. (1999a) *Oil palm and the environment – a Malaysian perspective*. Malaysian Oil Palm Growers' Council, Kuala Lumpur [1.4.2.4; 1.5.4; 8.1.7]
- Gurmit S., Kow D.L., Lee K.H., Lim K.C. & Loong S.G. (1999b) Empty fruit bunches as mulch. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 171–183, Malaysian Oil Palm Growers' Council, Kuala Lumpur [10.1.3.2; 11.6.1.1; 11.7.2.1; 11.7.4.1; 13.4.8.2]
- Hadcock M. (1983) It had to be simple, cheap, reliable and easy to clean. *Int. agric. Dev.*, **Jan./Feb.**, 16–18 [13.4.4]
- Haines W.B. (1959) The significance of cyclic peak yields in Nigeria in oil palms. *Emp. J. exp. Agric.*, **27**, 1–9 [4.4.2]
- Haines W.B. & Benzian B. (1956) Some manuring experiments on oil palm in Africa. *Emp. J. exp. Agric.*, **24**, 137–160 [4.4; 4.4.2; 5.2.3; 11.3.3.1]
- Haji Baba A.S., Azillah A., Mukherjee T.K. & Abdullah R.B. (1998) Growth and reproduction performance of small ruminants under integrated livestock–oil palm production systems. *Asian Austr. J. Anim. Sci.*, **11**, 573–579 [8.4.3.4]
- Hakim M., Harahap S. & Muluk C. (1998) Interplanting method in oil palm replanting programme: a new cost-effective approach. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 240–249, Indonesian Oil Palm Res. Inst., Medan, Indonesia [8.3.4.3; 9.4.2; 12.2.4.1]
- Haliza H.F., Masnita M.H., Ho C.L., Masani Mat Yunus A. & Parveez G.K.A. (2001) Construction of antisense desaturase gene transformation vectors for the production of high stearate transgenic oil palm. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 723–734, Malaysian Palm Oil Board, Kuala Lumpur [6.6.2.3]
- Hallett R.H., Gries G., Borden J.H., Czyzewska E., Oehlschlager A.C., Pierce H.D., Angerilli N.P.D. & Rauf A. (1993) Aggregation pheromones of two Asian palm weevils, *Rhynchophorus ferrugineus* (Oliv.) and *R. vulnerratus* (Panz.). *Naturwissenschaften*, **80**, 328–331 [12.2.6.1]
- Hallett R.H., Perez A.L., Gries G., Gries R., Pierce H.D., Yue J., Oehlschlager A.C., Gonzalez L.M. & Borden J.H. (1995) Aggregation pheromone of coconut rhinoceros beetle, *Oryctes rhinoceros* (L.) (Coleoptera: Scarabaeidae). *J. Chem. Ecol.*, **21**, 1549–1570 [12.2.4.1]
- Hamdan J., Burnham C.P. & Ruhana B. (1999) Evaluation of quantity–intensity relationships of potassium in deeply weathered soil profiles developed over granite from Peninsular Malaysia. *Commun. Soil Sci. Plant Anal.*, **30**, 2311–2321 [3.5.1.1]
- Hamdan J., Burnham C.P. & Ruhana B. (2000) Degradation effect of slope terracing on soil quality for *Elaeis guineensis* Jacq. (oil palm) cultivation. *Land Degrad. Develop.*, **11**, 181–193 [8.1.3.2; 8.3.5]
- Hamdan A.B., Tayeb Dolmat M., Zin Z.Z., Tarmizi Mohamad A. & Khalid H. (2001) Monitoring the long term effects of land application of palm oil mill effluent to oil palm on water quality. *Oil Palm Bull.*, **42**, 24–38 [11.7.2.2]
- Hamel P. (1986) Assessment of the risks of erosion in young oil palm plantations where food crop intercropping is practised, based on the Wischmeier and Smith equation. *Oléagineux*, **41**, 419–428 [3.4.3.8; 8.4.3.2]
- Han K.J. & Chew P.S. (1978) Control measures and observations in some *Valanga nigricornis* outbreaks in oil palms in Peninsular Malaysia. *Planter, Kuala Lumpur*, **54**, 682–691 [12.2]
- Han K.J. & Chew P.S. (1982) Growth and nutrient contents of leguminous covers in oil palm plantations in Malaysia. In: *The oil palm in agriculture in the eighties, Vol. 2*, (Ed. by E. Pushparajah & Chew P.S.), pp. 235–252, Incomp. Soc. Planters, Kuala Lumpur [10.1.2.3; 11.6.2.6]
- Hanold D. & Randles J.W. (1991) Detection of coconut cadang-cadang viroid-like sequences in oil and coconut palm and other monocotyledons in the south-west Pacific. *Ann. appl. Biol.*, **118**, 139–151 [12.1]
- Hansen L.D., Breidenbach R.W., Smith B.N., Hansen J.R. & Criddle R.S. (1998) Misconceptions about the relation between plant growth and respiration. *Bot. Acta*, **111**, 255–260 [4.1.4.3]
- Hardon J.J. (1969) Interspecific hybrids in the genus *Elaeis*. II. Vegetative growth and yield of F1 hybrids *E. guineensis* × *E. oleifera*. *Euphytica*, **18**, 380–388 [2.4; 5.3.7.1; 5.5.1.6]
- Hardon J.J. (1970) Inbreeding in populations of the oil palm (*Elaeis guineensis* Jacq.) and its effects on selection. *Oléagineux*, **25**, 449–456 [5.4.2.1; 5.4.2.2; 5.4.3]
- Hardon J.J. (1976) Oil palm breeding – introduction. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 89–108, Elsevier, Amsterdam [5.2.6.2; 5.3.3.2]
- Hardon J.J. & Corley R.H.V. (1976) Pollination. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 299–305, Elsevier, Amsterdam [4.4.7.1]
- Hardon J.J. & Corley R.H.V. (2000) Breeding of perennial tree crops – lessons for the future. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 41–57, Incomp. Soc. Planters, Kuala Lumpur [5.6; 6.6.3]
- Hardon J.J. & Davies M.D. (1969) Effects of vacuum-drying on the viability of oil palm pollen. *Expl. Agric.*, **5**, 59–65 [5.2.1.2]
- Hardon J.J. & Ooi S.C. (1971) To what extent should inbreeding be avoided in oil palm seed production? *Comm. (Agron.) Chemara Res. Stn.*, **9**, 1–11 [5.4.3]
- Hardon J.J. & Tan G.Y. (1969) Interspecific hybrids in the genus *Elaeis*. I. Crossability, cytogenetics and fertility of F1 hybrids of *E. guineensis* × *E. oleifera*. *Euphytica*, **18**, 372–379 [2.4]
- Hardon J.J. & Thomas R.L. (1968) Breeding and selection of the

- oil palm in Malaya. *Oléagineux*, **23**, 85–90 [5.1.1.1; 5.1.1.2; 5.3.2; 5.5.2.2]
- Hardon J.J. & Turner P.D. (1967) Observations on natural pollination in commercial plantings of oil palm (*Elaeis guineensis*) in Malaya. *Expl Agric.*, **3**, 105–116 [2.2.2.3]
- Hardon J.J., Williams C.N. & Watson I. (1969) Leaf area and yield in the oil palm in Malaya. *Expl Agric.*, **5**, 25–32 [4.1.3; 4.1.4.2; 4.3.5]
- Hardon J.J., Corley R.H.V. & Ooi S.C. (1972) Analysis of growth of oil palm 2. Estimation of genetic variances of growth parameters and yield of fruit bunches. *Euphytica*, **21**, 257–264 [4.3.8; 5.2.5; 5.3.2; 5.3.4.1]
- Hardon J.J., Hashim M. & Ooi S.C. (1973) Oil palm breeding – a review. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 23–87, Incomp. Soc. Planters, Kuala Lumpur [5.1.6.2; 5.4.2.1]
- Hardon J.J., Gascon J.P., Noiret J.M., Meunier J., Tan G.Y. & Tam T.K. (1976) Major oil palm breeding programmes. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 109–125, Elsevier, Amsterdam [5.1.2; 5.1.6.1]
- Hardon J.J., Corley R.H.V. & Lee C.H. (1987) Breeding and selecting the oil palm. In: *Improving vegetatively propagated crops* (Ed. by A.J. Abbott & R.K. Atkin), pp. 63–81, Academic Press, London [5.3.2; 5.4.5.1; 5.5.1.1; 5.5.2.2; 6.4.1]
- Härdter R., Woo Y.C. & Ooi S.H. (1997) Intensive plantation cropping, a source of sustainable food and energy production in the tropical rain forest areas in Southeast Asia. *Forest Ecol. Manage.*, **91**, 93–102 [1.4.3.1; 1.5.4; 8.4.3.2]
- Hargreaves N. (1985) Trade requirements of palm kernel and coconut oils. In: *'Palm kernel and coconut oils', Symp. Proc. No. 32*, pp. 3–12, British Food Manufacturing Industries Assoc., Leatherhead [13.4.6.3]
- Hartley C.W.S. (1957) Oil palm breeding and selection in Nigeria. *J. W. Afr. Inst. Oil Palm Res.*, **2**, 108–115 [5.1.5]
- Hartley C.W.S. (1965) Some notes on the oil palm in Latin America. *Oléagineux*, **20**, 359–363 [12.1.7.2]
- Hartley C.W.S. (1977) *The oil palm*, 2nd edn, Longman, London.
- Hartley C.W.S. (1988) *The oil palm*, 3rd edn, Longman, London.
- Hartley M.J. (2002) Rationale and methods for conserving biodiversity in plantation forests. *Forest Ecol. Management*, **155**, 81–95 [8.2.1]
- Haryati T., Man Y.B.C., Jinap S., Ghazali H.M. & Buana L. (1998) Optimization of chemical transesterification of palm oil using response surface methodology. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 423–431, Indonesian Oil Palm. Res. Inst., Medan, Indonesia [14.3.3.1]
- Hasan Y. & Turner P.D. (1994) Research at Bah Lias Research Station on basal stem rot of oil palm. In: *Proc. Int. Workshop 'Perennial crop diseases caused by Ganoderma'* (Ed. by M. Holderness), CAB International, Wallingford [12.1.6.3]
- Hasan Y. & Turner P.D. (1998) The comparative importance of different oil palm tissues as infection sources for basal stem rot in replantings. *Planter, Kuala Lumpur*, **74**, 119–135 [12.1.6.3]
- Hashim M.T. (1993) Paclobutrazol – a growth and flowering regulator of young oil palm. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 85–94, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.4.4.2]
- Hashim M.T. & Yeow K.H. (1987) Effect of frond removal on fresh fruit bunches production. In: *Proc. Natn. Symp. 'Oil palm by-products for agro-based industries'*, pp. 227–241, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.6.1]
- Hashim M.T., Tam T.K. & Yeow K.H. (1988a) Field evaluation of oil palm advanced planting material. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 391–395, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [7.2.3; 9.2.1]
- Hashim M.T., Yeow K.H. & Poon Y.C. (1988b) Recent development in nursery practice – potting media. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 369–371, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [7.2.3]
- Hashim M.T., Teoh C.H., Kamarudzan A. & Mohd Ali A. (1995) Zero burning – an environmentally friendly replanting technique. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 185–194, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.2]
- Hassan H.H. (1985) Land capability evaluation for oil palm cultivation in Bangladesh. *Bano Biggyau Patrika*, **11**, 1–9 [3.1]
- Hasselo H.N. (1959) Fertilising of young oil palms in the Cameroons. *Pl. Soil*, **11**, 113–130 [12.1.5.1]
- Hastert R.C. (1996) Hydrogenation – a technology update. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century' – Chemistry and technology* (Ed. by Badri Muhammad *et al.*), pp. 303–313, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.3.3.2]
- Hayes K.C. & Khosla P. (1992) Dietary fatty acid thresholds and cholesterolemia. *FASEB J.*, **6**, 2600–2607 [14.4.1]
- Hemptinne J. & Ferwerda J.D. (1961) Influence des précipitations sur les productions du palmier à huile (*Elaeis* Jacq.). *Oléagineux*, **16**, 431–437 [4.4; 4.5.3; 4.5.4]
- Henderson A. (1986a) A review of pollination studies in the Palmae. *Bot. Rev.*, **52**, 221–259 [2.2.2.5]
- Henderson A. (1986b) *Barcella odora*. *Principes*, **30**, 74–76 [2.1]
- Henderson J. (1998) *Ripening and abscission in fruit of the oil palm (Elaeis guineensis Jacq.) – a biochemical investigation*. Thesis, Open Univ., Oxford Research Unit, Oxford [2.2.2.7]
- Henderson J. & Osborne D.J. (1990) Cell separation and anatomy of abscission in the oil palm, *Elaeis guineensis* Jacq. *J. exp. Bot.*, **41**, 203–210 [2.2.2.7]
- Henderson J. & Osborne D.J. (1991) Lipase activity in ripening and mature fruit of the oil palm. Stability *in vivo* and *in vitro*. *Phytochemistry*, **30**, 1073–1078 [13.3.3]
- Henderson J. & Osborne D.J. (2000) The oil palm in all our lives: how this came about. *Endeavour*, **24**, 63–68 [1.2.3]
- Henderson J., Davies H.A., Heyes S.J. & Osborne D.J. (2001) The study of a monocotyledon abscission zone using microscopic, chemical, enzymatic and solid state C-13 CP/MAS NMR analyses. *Phytochemistry*, **56**, 131–139 [2.2.2.7; 6.6.2.1]
- Henry P. (1948a) Un *Elaeis* remarquable: le palmier à huile vivipare. *Rev. Int. Bot. appl. Agric. Trop.*, **28**, 422–427 [2.2.1.4]
- Henry P. (1948b) Les facteurs de pollinisation chez le palmier à huile. *Oléagineux*, **3**, 587–589 [2.2.2.5]
- Henry P. (1951) La germination des graines d'*Elaeis*. *Rev. Int. Bot. appl. Agric. Trop.*, **31**, 565–591 [2.2.1; 7.1.4.4]
- Henry P. (1952) La germination des graines d'*Elaeis*. *Rev. Int. Bot. appl. Agric. Trop.*, **32**, 66–77 [7.1.4.4]
- Henry P. (1955a) Morphologie de la feuille d'*Elaeis* au cours de sa croissance. *Rev. gén. Bot.*, **62**, 319–323 [2.2.1.4]
- Henry P. (1955b) Note préliminaire sur l'organisation foliaire chez le palmier à huile. *Rev. gén. Bot.*, **62**, 127–135 [2.2.1.3]

- Henry P. (1955c) Sur le développement des feuilles chez le palmier à huile. *Rev. gén. Bot.*, **62**, 231–237 [2.2.1.4]
- Henry P. (1958) Croissance et développement chez *Elaeis guineensis* Jacq. de la germination à la première floraison. *Rev. gén. Bot.*, **66**, 5–34 [3.2.1]
- Henry P. (1959) Prolongation de la viabilité du pollen chez *Elaeis guineensis*. *C. R. Hebd. Séances Acad. Sci., Paris*, **98**, 722–724 [5.2.1.2]
- Henry P. (1960) Recherches cytologiques sur l'appareil floral et la graine chez *Elaeis guineensis* et *Cocos nucifera*. I. La formation de l'appareil floral. *Rev. gén. Bot.*, **68**, 111–132 [4.4; 4.4.3.2; 4.4.5.2; 4.4.8]
- Henry P. & Gascon J.P. (1950) Les palmiers à huile du type *pisifera* et la stérilité. *Oléagineux*, **5**, 29–34 [2.2.2.6; 5.4.2.3]
- Henry P. & Scheidecker D. (1953) Nouvelle contribution à l'étude des *Elaeis vivipares*. *Oléagineux*, **8**, 681–688 [2.2.1.4]
- Henson I.E. (1990a) Retardation of inflorescence growth in oil palm. *Trans. Malay. Soc. Pl. Physiol.*, **1**, 207–214 [4.4.5.4]
- Henson I.E. (1990b) Photosynthesis and source-sink relationships in oil palm (*Elaeis guineensis*). *Trans. Malay. Soc. Pl. Physiol.*, **1**, 165–171 [4.2.2.1; 4.2.2.2; 4.3.6.2]
- Henson I.E. (1991a) Limitations to gas exchange, growth and yield of young oil palm by soil water supply and atmospheric humidity. *Trans. Malay. Soc. Pl. Physiol.*, **2**, 39–45 [4.3.3.2; 4.4.3.1; 10.3.1.2]
- Henson I.E. (1991b) Use of leaf temperature measurements for detection of stress conditions in oil palm. *Trans. Malay. Soc. Pl. Physiol.*, **2**, 51–57 [4.4.5.4]
- Henson I.E. (1991c) Adaptation to light environment by leaves of oil palm (*Elaeis guineensis*). *Palm Oil Res. Inst. Malaysia, Bull.*, **22**, 1–8 [4.1.4.3; 4.3.1.2; 4.3.6.2]
- Henson I.E. (1991d) Age-related changes in stomatal and photosynthetic characteristics of leaves of oil palm (*Elaeis guineensis* Jacq.). *Elaeis*, **3**, 336–348 [2.2.1.2; 2.2.1.4; 4.2.2.1]
- Henson I.E. (1992) Carbon assimilation, respiration and productivity of young oil palm (*Elaeis guineensis*). *Elaeis*, **4**, 51–59 [4.1.4.3]
- Henson I.E. (1993) Assessing frond dry matter production and leaf area development in young oil palms. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 473–478, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.1.3; 4.1.4.2]
- Henson I.E. (1995a) Carbon assimilation, water use and energy balance of an oil palm plantation assessed using micrometeorological techniques. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 137–158, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.2.2.1; 3.2.4; 4.1.2; 4.1.4.2; 4.1.4.3; 4.3.3.2; 4.3.3.4]
- Henson I.E. (1995b) Photosynthesis, dry matter production and yield of oil palm under light-limiting conditions. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 525–541, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.1.4.3; 10.3.1.1]
- Henson I.E. (1997) Analysis of oil palm productivity. I. The estimation of seasonal trends in bunch dry matter production. *Elaeis*, **9**, 69–77 [4.2.2.3]
- Henson I.E. (1998a) Notes on oil palm productivity. I. Productivity at two contrasting sites. *J. Oil Palm Res.*, **10**, 57–67 [4.4]
- Henson I.E. (1998b) Notes on oil palm productivity. II. An empirical model of canopy photosynthesis based on radiation and atmospheric vapour pressure deficit. *J. Oil Palm Res.*, **10**, 25–28 [4.3.3.2; 4.5.5]
- Henson I.E. (1999a) Notes on oil palm productivity. IV. Carbon dioxide gradients and fluxes and evapotranspiration, above and below the canopy. *J. Oil Palm Res.*, **11**, 33–40 [3.2.4]
- Henson I.E. (1999b) Notes on oil palm productivity. V. Evaluation of alternative mechanisms for supporting seasonal variation in dry matter production. *J. Oil Palm Res.*, **11**, 50–61 [4.2.2.4]
- Henson I.E. (1999c) Comparative ecophysiology of oil palm and tropical rainforest. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 9–39, Malay. Oil Palm Growers' Council, Kuala Lumpur [8.2.1; 10.1.3.2; 11.1.4; 11.6.1.1; 11.7.1; 11.7.4.1]
- Henson I.E. (2000) Modelling the effects of 'haze' on oil palm productivity and yield. *J. Oil Palm Res.*, **12**, 123–134 [3.2.4; 4.1.4.3]
- Henson I.E. & Chai S.H. (1997) Analysis of oil palm productivity. II. Biomass, distribution, productivity and turnover of the root system. *Elaeis*, **9**, 78–92 [4.1.2.3; 4.2.1.4; 11.2.1.4]
- Henson I.E. & Chai S.H. (1998) Analysis of oil palm productivity. III. Seasonal variation in assimilate requirements, assimilation capacity, assimilate storage and apparent photosynthetic conversion efficiency. *J. Oil Palm Res.*, **10**, 35–51 [4.2.2.3; 4.2.2.4; 4.5.5]
- Henson I.E. & Chang K.C. (1990) Evidence for water as a factor limiting performance of field palms in West Malaysia. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 487–498, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.3.3; 4.3.3.3; 4.4.3.1; 10.3.1.2]
- Henson I.E. & Chang K.C. (2000) Oil palm productivity and its component processes. In: *Advances in oil palm research*, Vol. I (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 97–145, Malaysian Palm Oil Board, Kuala Lumpur [4.1.4.3; 4.3.3; 4.3.5.2]
- Henson I.E., Jamil Z.M. & Dolmat M.T. (1992) Regulation of gas exchange and abscisic acid concentrations in young oil palm (*Elaeis guineensis*). *Trans. Malay. Soc. Pl. Physiol.*, **3**, 29–34 [4.3.3.2; 4.4.4.2; 10.3.2.1]
- Henson I.E., Chang K.C. & Haniff Harun M. (1994) Physiology. In: *Palm Oil Res. Inst. Malaysia Sci. Rep.* **7**, pp. 204–265 [2.2.1.5]
- Henson I.E., Chang K.C., Siti Nor Aishah Mustakim, Chai S.H., Hasnuddin M.Y. & Zakaria Abas (1999) The oil palm trunk as a carbohydrate reserve. *J. Oil Palm Res.*, **11**, 98–113 [4.2.2.4]
- Herrera J., Alizaga R. & Guevara E. (1998) Use of chemical treatments to induce seed germination in oil palm (*Elaeis guineensis* Jacq.). *ASD Oil Palm Papers*, **18**, 1–16 [7.1.1.3]
- Hertel D. & Leuschner C. (2002) A comparison of four different fine root production estimates with ecosystem carbon balance data in a *Fagus/Quercus* mixed forest. *Pl. & Soil*, **239**, 237–251 [11.2.1.2; 11.2.1.4]
- Heru S.B., Siburian J., Wanasuria S., Chong K.C. & Thiagarajan S. (2000) Large scale use of barn owl (*Tyto alba*) for controlling rat population in oil palm plantations in Riau, Sumatra. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 529–544, Incorp. Soc. Planters, Kuala Lumpur [12.3.1]
- Hew C.K. & Tam T.K. (1969) A comparison of oil palm nursery techniques. In: *Progress in oil palm* (Ed. by P.D. Turner), pp. 38–48, Incorp. Soc. Planters, Kuala Lumpur [7.2]
- Hew C.K. & Tam T.K. (1971) *Annual Report, Research &*

- Advisory Scheme, 1970*. Harrisons & Crosfield (Malaysia) Sdn Bhd [9.1.1]
- Hew C.K., Ng S.K. & Lim K.P. (1973) The rationalisation of manuring oil palms and its economics in Malaysia. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 306–323, Incomp. Soc. Planters, Kuala Lumpur [11.3.2.3]
- Hirsch P.J. (1980) Relations entre l'appareil végétatif et la production chez le palmier à huile en Côte d'Ivoire. *Oléagineux*, **35**, 233–239 [4.1.3.1; 4.1.3.3; 4.3.8; 5.2.2; 5.4.4]
- Hirsinger F., Schick K.P. & Stalmans M. (1995) A life-cycle inventory for the production of oleochemical raw materials. *Tenside Surf. Det.*, **32**, 420–432 [14.3.6.1]
- Ho C.C., Lim A.L., Agamuthu P., Nizar A., Ramien A. & Theivendirarajah K. (1991) *The cellular basis and possible cause for the development of mantled flower in oil palm derived from tissue culture*. Paper presented at Natn. Seminar 'Intensification of research in priority areas', 16–19 Dec., Penang [6.3.1.2]
- Ho C.T. (1996) The integrated management of *Oryctes rhinoceros* (L) populations in the zero burning environment. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 336–368, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.4.1]
- Ho C.T. (1998) Safe and efficient management systems for plantation pests and diseases. *Planter, Kuala Lumpur*, **74**, 369–385 [12.1.6.3; 12.2.1.1; 12.2.5.2]
- Ho C.T. & Khairudin H. (1997) Usefulness of soil mounding treatments in prolonging productivity of prime-aged *Ganoderma* infected palms. *Planter, Kuala Lumpur*, **73**, 239–244 [12.1.6.3]
- Ho C.T. & Sidhu M. (1986) Some developments in chemical control of leaf pests of oil palm in East and Peninsula Malaysia. In: *Abstracts, 2nd Int. Conf. 'Plant protection in the tropics'*, pp. 177–187, Malaysian Plant Protection Soc., Kuala Lumpur [12.2.5.1]
- Ho C.T. & Teh C.L. (1997) Integrated pest management in plantation crops in Malaysia: challenges and realities. In: *Plantation management for the 21st century* (Ed. by E. Pushparajah), pp. 125–149, Incomp. Soc. Planters, Kuala Lumpur [12.2.1; 12.3.1; 12.3.2]
- Ho C.Y., Gan L.T., Tek C.Y.J., Singh S., Hon D. & Tan M.C. (1996) Effects of harvesting standards, *dura* contamination, palm age and environmental differences on recent oil extraction rates. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 221–237, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.5.2; 10.5; 10.5.2]
- Ho S.H. & Chiang K.L. (1999) Replanting strategies for oil palms in Sabah. *Planter, Kuala Lumpur*, **75**, 9–20 [8.3.4.2]
- Ho Y.W. (1999) Cloning of *E. oleifera* × *E. guineensis* hybrid. *Int. Soc. Oil Palm Agron. Newsletter*, **8**, 4–5 [5.5.1.6]
- Ho Y.W. & Tan Y.P. (1990) Experiences with oil palm clones. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 66–72, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.1.1]
- Ho Y.W., Varghese G. & Taylor G.S. (1985) Pathogenicity of *Fusarium oxysporum* isolates from Malaysia and *F. oxysporum* f.sp. *elaedis* from Africa to seedlings of oil palm (*Elaeis guineensis*). *Phytopath. Z.*, **114**, 193–202 [12.1.6.2]
- Hochberg M.E. & Waage J.K. (1991) A model for the biological control of *Oryctes rhinoceros* (Coleoptera: Scarabaeidae) by means of pathogens. *J. appl. Ecol.*, **28**, 514–531 [12.2.4.1]
- Holliday R. (1960) Plant population and crop yield: Part I. *Field Crop Abs.*, **13**, 159–167 [9.3.3.1]
- Hong T.K. (1979) *Effects of some environmental factors on photosynthesis and productivity of oil palm seedlings*. Thesis, Univ. of Malaya, Kuala Lumpur [4.1.4.3]
- Hong T.K. & Corley R.H.V. (1976) Leaf temperature and photosynthesis of a tropical C3 plant, *Elaeis guineensis*. *Malay. agric. Res. Dev. Inst. Res. Bull.*, **4** (1), 16–20 [4.3.4]
- Hoong H.K. (2000) The introduction of barn owl (*Tyto alba*) to Sabah for rat control in oil palm plantations. *Planter, Kuala Lumpur*, **76**, 215–222 [12.3.1]
- Hoong H.K. & Donough C.R. (1998) Recent trends in oil extraction rate (OER) and kernel extraction rate (KER) in Sabah. *Planter, Kuala Lumpur*, **74**, 181–202 [4.5.2]
- Hoong H.W. (2000) Oil palm fruit (FFB) evacuation in hilly areas – with special reference to the 'Sawit cable system'. *Planter, Kuala Lumpur*, **76**, 459–467 [8.2.2; 10.4.6]
- Hornus P. & Nguimjeu E. (1992) Use of empty bunches for fertilisation in oil palm plantations. *Oléagineux*, **47**, 250–254 [8.3.3.2; 9.4.2; 11.1.3.1]
- Houmiel K.L., Slater S., Broyles D., Casagrande L., Colburn S., Gonzalez K., Mitsky T.A., Reiser S.E., Shah D., Taylor N.B., Tran M., Valentin H.E. & Gruys K.J. (1999) Poly(beta-hydroxybutyrate) production in oilseed leucoplasts of *Brassica napus*. *Planta*, **209**, 547–550 [6.6.3]
- Houssou M., Omere A. & Meunier J. (1989) *Breeding for drought resistance in the oil palm 1. Variability of some crosses for their productivity and their mortality*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [5.1.3.1; 5.3.6.1]
- Huger A.M. (1966) A virus disease of the Indian rhinoceros beetle, *Oryctes rhinoceros* (Linnaeus), caused by a new type of insect virus, *Rhabdionvirus oryctes* gen.n., sp. n. *J. Invertebrate Pathol.*, **8**, 38–51 [12.2.4.1]
- Hughes W.A., Bociek S.M., Barrett J.N. & Ratcliffe R.G. (1983) An investigation of the growth characteristics of oil palm (*Elaeis guineensis*) suspension cultures using ³¹P NMR. *Biosci. Rep.*, **3**, 1141–1148 [6.5.1.1]
- Huguenot R. (1963) Coup mécanique des souches et andainage sur sol de forêt. *Oléagineux*, **18**, 623–625 [8.3.3.2]
- Huguenot R. & Vera J. (1981) Description et lutte contre *Castnia daedalus* Cr. (Lep. Castniidae) ravageur du palmier à huile en Amérique du Sud. *Oléagineux*, **36**, 543–548 [12.2.8.2]
- Huntley R.P. (1995) *Cytokinins and gibberellins in oil palm sex determination*. Thesis, Univ. of Cambridge, Cambridge [4.4.4.2]
- Hurtado J.R. & Ramos Nunez G. (1970) Estudio de la palmera noli (*Elaeis melanococca* Gaert.) y preliminares de su fitomejoramiento en Colombia. *Acta Agron.*, **20**, 9–23 [2.3.2]
- Husain Z., Zainac Z. & Abdullah Z. (2002) Briquetting of palm fibre and shell from the processing of palm nuts to palm oil. *Biomass & Bioenergy*, **22**, 505–509 [13.4.8.2]
- Hussey G. (1958) An analysis of the factors controlling the germination of the seed of the oil palm, *Elaeis guineensis* (Jacq.). *Ann. Bot.*, **22**, 259–286 [2.2.1; 7.1]
- Hussey G. (1959) The germination of oil palm seed: experiments with *tenera* nuts and kernels. *J. W. Afr. Inst. Oil Palm Res.*, **2**, 331–354 [7.1]
- Hussin A. (1995) Ammonia volatilisation loss from surface placed

- urea-treated POME pellets. *Pertanika J. Trop. Agric. Sci.*, **18**, 103–107 [11.7.4.2]
- Hutagalung R.I., Mahyuddin M. & Syed Jalaludin (1982) Feeds for farm animals from the oil palm. In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 609–622, Incomp. Soc. Planters, Kuala Lumpur [13.6.3]
- Hutomo T. & Pamin K. (1995) Contribution of SP540 in the oil palm breeding programmes in Indonesia. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani et al.), pp. 78–83, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.3; 5.5.1.2]
- Hutomo T., Razak Purba A. & Pamin K. (1996) Progress of oil palm breeding in IOPRI. Current results and strategy for the future. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin et al.), pp. 55–61, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.4.2]
- Huxley P. (1999) *Tropical agroforestry*, Blackwell Science, Oxford [8.4.3.2]
- Idris A.S., Ariffin D., Watt T.A. & Swinburne T.R. (2001) Distribution of species of *Ganoderma* basal stem rot of oil palms in relation to the environmental conditions in Peninsular Malaysia. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 385–394, Malaysian Palm Oil Board, Kuala Lumpur [12.1.6.3]
- Ilechic C.O. & Omoti U. (2001) *Small scale oil palm fruit processing in Nigeria*. Paper presented at Conf. 'The future of the oil palm industry in Africa and strategies for development', African Oil Palm Development Association/African Development Bank, 12th Sept., Abidjan [1.4.3.4]
- ICAE (Int. Comm. agric. Engineers) (1999) *Plant production engineering, Vol III*. (Ed. by B.A. Stoute & B. Cheze). Amer. Soc. agric. Engineers, St Joseph, Minnesota [10.4.7]
- IPCC (2001) *Climate change 2001. 1. Scientific basis. 2. Impacts, adaptation and vulnerability. 3. Mitigation*, Cambridge University Press, Cambridge, UK [3.3.2; 8.1.2; 11.7.4.2; 15.3.2]
- IRHO (1970) *Rapport d'activités, 1970*, Inst. Rech. Huiles Oléagineux, Paris [4.4.4.1]
- IRHO. (1974) *Rapport d'activités, 1972–3*. Inst. Rech. Huiles Oléagineux, Paris [11.4.2.2]
- IRHO (1976) Protection of young palms against rats. *Oléagineux*, **31**, 165–168 [12.3.1]
- IRHO (1986a) The oil palm prenursery. 1. From creation to pricking out of germinated seeds. *Oléagineux*, **41**, 429–435 [7.2.1.1]
- IRHO (1986b) The oil palm prenursery. 2. Crop techniques. *Oléagineux*, **41**, 491–498 [7.2.1.1]
- IRHO (1992a) Potassium deficiency in oil palm. Symptoms, and correction. *Oléagineux*, **47**, 587–591 [11.4.1.2]
- IRHO (1992b) Activity report 1989–1991: crop protection – oil-palm and coconut. *Oléagineux*, **47**, 360–378 [12.1.4; 12.1.6.2; 12.1.6.4; 12.1.7.2]
- IRHO (1992c) Activity report 1989–1991: oil palm. *Oléagineux*, **47**, 289–326 [9.3.3.1]
- Isenmila A.E. (1993) Oil palm growth, water use and yield response to depths of fertiliser placement. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron et al.), pp. 312–318, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.2.1.3]
- Ismael B.S., Tasrif A., Sastroulomo S.S. & Latiff A. (1995) Weed seed population in rubber and oil palm plantations with legume cover crops. *Pl. Protection Q.*, **10**, 20–23 [10.1.2.2]
- Ismail S., Wood B.J. & Ng S.K. (1985a) The problem of stripping oil palm bunches and some approaches to dealing with it. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 235–254, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.5.2]
- Ismail S., Wood B.J. & Tan S.T. (1985b) An investigation of the oil palm bunch analysis technique as a guide to actual oil content. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 110–128, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2.4.2]
- Ismail S., Tan S.T., Ng W.K., Ng S.K. & Wood B.J. (1987) A pilot exercise in milling FFB from *Elaeis oleifera* × *E. guineensis* hybrid oil palms. *Int. Soc. Oil Palm Breeders Newslett.*, **4** (2), 11 [5.5.1.6]
- Jack H.W. & Jagoe R.B. (1932) Variation in fruiting ability of oil palms. *Malay. agric. J.*, **20**, 14–19 [5.1.1.1; 5.1.1.2]
- Jack P.L., James C., Price Z., Groves L., Corley R.H.V., Nelson S. & Rao V. (1998) Application of DNA markers in oil palm breeding. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika et al.), pp. 315–324, Indonesian Oil Palm Res. Inst., Medan, Indonesia [5.2.8.3]
- Jacobsberg B. (1975) Characteristics of Malaysian palm oil. *Oléagineux*, **30**, 271–276 [13.1.3]
- Jacobsberg B. & Jacqmain D. (1973) Palm oil quality. Appreciation and forecast of stability of crude palm oil during transport and storage. *Oléagineux*, **28**, 25–32 [13.4.6.2]
- Jacobsberg B., Deldime P. & Gapor A. (1978) Tocopherols and tocotrienols in palm oil. Considerations on their role as antioxidants and practical determinations. *Oléagineux*, **33**, 239–247 [13.4.6.2]
- Jacquemard J.C. (1979) Contribution to the study of the height growth of the stems of *Elaeis guineensis* Jacq. Study of the L2T × D10D cross. *Oléagineux*, **34**, 492–497 [2.2.1.3; 4.2.1.1; 4.2.1.3]
- Jacquemard J.C. (1998) *Oil palm*, Macmillan Education, London [7; 8; 9; 10; 12]
- Jacquemard J.C. & Durand-Gasselin T. (1999) Production of improved oil palm (*Elaeis guineensis* Jacq.) planting materials from seed and clonal methods. In: *Proc. Seminar 'Science of oil palm breeding' (Montpellier, 1992)* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 112–130, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.5.3]
- Jacquemard J.C. & Jannot C. (1999a) The changing oil palm sector in Indonesia I. Sectoral growth (1848–1996). *Plantations, Recherche, Développement*, **6**, 303–331 [1.4.3.1]
- Jacquemard J.C. & Jannot C. (1999b) The changing oil palm sector in Indonesia II. Has the sector found a second wind? *Plantations, Recherche, Développement*, **6**, 385–399 [1.4.3.1]
- Jacquemard J.C., Meunier J. & Bonnot F. (1982) Genetic study of the reproduction of an *Elaeis guineensis* oil palm cross. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 19–32, Incomp. Soc. Planters, Kuala Lumpur [5.5.2; 5.5.2.3]
- Jacquemard J.C., Baudouin L. & Noiret J.M. (1997) Le palmier à huile. In: *L'amélioration des plantes tropicales* (Ed. by A. Charrier et al.), pp. 507–532, CIRAD, Montpellier [5.2.8.3; 5.5.2.3]
- Jacquemard J.C., Edyana Suryana H., Asmady H. & Desmier de Chenon R. (2002a) *Oil palm (Elaeis guineensis Jacq.) and Oryctes rhinoceros L.: planting material effect*. Paper presented

- at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [12.2.4.1]
- Jacquemard J.C., Tailliez B., Dadang K., Ouvrier M. & Asmady H. (2002b) *Oil palm* (*Elaeis guineensis* Jacq.) nutrition: planting material effect. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [11.4.4.2]
- Jacquin N.J. (1763) *Selectarum stirpium*. Americanarum historia. [2.1; 2.2]
- Jagoe R.B. (1934) Notes on the oil palm in Malaya with special reference to floral morphology. *Malay. agric. J.*, **22**, 541–549 [2.2.1.3]
- Jagoe R.B. (1952a) The ‘dumpy’ oil palm. *Malay. agric. J.*, **35**, 12–21 [2.2.1.3; 5.1.1.2]
- Jagoe R.B. (1952b) Deli oil palms and early introductions of *Elaeis guineensis* to Malaysia. *Malay. agric. J.*, **35**, 3–11 [5.1.1.1]
- Jalani B.S. (1998) Research and development of oil palm towards the next millennium. In: *Proc. 1998 Int. Oil Palm Conf. ‘Commodity of the past, today and the future’* (Ed. by A. Jatmika *et al.*), pp. 93–109, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.3.1; 1.4.1; 1.4.2; 1.4.3.2]
- Jalani B.S. & Rajanaidu N. (2000) Improvement in oil palm: yield, composition and minor components. *Lipid Tech.*, **12**, 5–8 [13.1.4]
- Jalani B.S., Chan K.W. & Ariffin D. (1999) Systems approach to potential products from biomass in oil palm. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 402–413, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.6.3.2]
- Jalani B.S., Chan K.W., Rajanaidu N. & Ariffin D. (2001) *Review of the stagnating yield in oil palm plantations and its possible remedies*. Paper presented at 2001 Int. Palm Oil Congr. – Agriculture, Malaysian Palm Oil Board, 20–22 Sept., Kuala Lumpur [1.4.3.2; 8.3.4.1; 10.5.2; 10.5.3; 10.6.2]
- Jaligot E., Rival A., Beulé T., Dussert S. & Verdeil J.L. (2000) Somaclonal variation in oil palm (*Elaeis guineensis* Jacq.): the DNA methylation hypothesis. *Pl. Cell Rep.*, **19**, 684–690 [6.3.1.2; 6.3.3]
- Jaligot E., Beulé T. & Rival A. (2002) Methylation-sensitive RFLPs: characterisation of two oil palm markers showing somaclonal variation-associated polymorphism. *Theor. Appl. Genet.*, **104**, 1263–1269 [6.3.3]
- Jamaluddin Nasir, Pupathy U.T. & Rahim Othman A. (2000) Golden Hope’s experience in managing saline soils for oil palm cultivation. In: *Proc. Int. Planters Conf. ‘Plantation tree crops in the new millennium: the way ahead’* (Ed. by E. Pushparajah), pp. 341–346, Incorp. Soc. Planters, Kuala Lumpur [3.4.3.4]
- Janssen A.W.B. (1959) *Miscellaneous notes on estate agriculture in Sumatra 7. Oil palm productivity and genetics*. Chemara Res. Sta. Internal Report [5.1.5; 5.3.3.3]
- Janssens P. (1927) Le palmier à huile au Congo Portugais et dans l’enclave de Cabinda. Descriptions des principales variétés de palmier (*Elaeis guineensis*). *Bull. agric. Congo Belge*, **18**, 29–58, 59–92 [2.2; 2.2.2.6]
- Jiménez O.D. & Reyes R. (1977) Estudio de una necrosis foliar que afecta varias plantaciones de palma de aceite (*Elaeis guineensis* Jacq.) en Colombia. *Fitopatología Colombiana*, **6**, 15–32 [12.1.5.2]
- Jinap S., Ali A.A., Man Y.B.C. & Suria A.M. (2000) Use of palm mid-fraction in dark chocolate as base filling centre at different storage temperatures. *Int. J. Food Sci. Nutr.*, **51**, 489–499 [14.3.1]
- Jinks J.L. & Lawrence M.J. (1983) The genetical basis of inbreeding depression and of heterosis: its implications for plant and animal breeding. *Palm Oil Res. Inst. Malaysia, Occ. Paper*, **11**, 1–8 [5.4.2.5; 5.4.3]
- Johnston T.J.M., Gurmit S., Loh H.P. & Lim K.C. (1994) On-ground experience of aerial fertiliser application in Malaysia. In: *‘Management for enhanced profitability in plantations’* (Ed. by Chee K.H.), pp. 307–313, Incorp. Soc. Planters, Kuala Lumpur [11.9.3]
- Jollands P. (1983) Laboratory investigations on fungicides and biological agents to control three diseases of rubber and oil palms and their potential applications. *Trop. Pest Manage.*, **29**, 33–38 [12.1.6.3]
- Jones L.H. (1974) Propagation of clonal oil palms by tissue culture. *Planter, Kuala Lumpur*, **50**, 374–381 [6.1]
- Jones L.H. (1989) Prospects for biotechnology in oil palm (*Elaeis guineensis*) and coconut (*Cocos nucifera*) improvement. In: *Biotechnology and Genetic Engineering Reviews*, Vol. 7 (Ed. by G.E. Russell & M.P. Tombs), pp. 281–296, Intercept, Andover [6.6.1.1]
- Jones L.H. (1990) Endogenous cytokinins in oil palm (*Elaeis guineensis* L.) callus, embryoids and regenerant plants measured by radioimmunoassay. *Pl. Cell Tissue Organ Culture*, **20**, 201–209 [6.2.3]
- Jones L.H. (1995) Clonal propagation of oil palm, past, present and future: a personal view. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 1–20, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.1; 6.2.1.2; 6.3.1.2]
- Jones L.H. (1997) The effects of leaf pruning and other stresses on sex determination in the oil palm and their representation by a computer simulation. *J. Theor. Biol.*, **187**, 241–260 [4.4.9; 4.5.5]
- Jones L.H. (1998) Metabolism of cytokinins by tissue culture lines of oil palm (*Elaeis guineensis* Jacq.) producing normal and abnormal flowering palms. *J. Pl. Growth Reg.*, **17**, 205–213 [6.3.1.2]
- Jones L.H. & Hanke D.E. (1992) Kinetin-9-glucoside is a major metabolite of kinetin in oil palm cultures. In: *Proc. Int. Symp. ‘Physiology and biochemistry of cytokinins in plants’* (Ed. by M. Kamínek, D.W.S. Mok & E. Zazimalová), pp. 65–68, SPB Academic Publishing, The Hague [6.3.1.2]
- Jones L.H., Barfield D., Barrett J.N., Flook A., Pollock K. & Robinson P. (1982) Cytology of oil palm cultures and regenerant plants. In: *Proc. 5th Int. Congr. ‘Plant tissue and cell culture’*, pp. 727–728, Tokyo, 1981 [6.3]
- Jones L.H., Hanke D.E. & Eeuwens C.J. (1995) An evaluation of the role of cytokinins in the development of abnormal inflorescences in oil palms (*Elaeis guineensis* Jacq.) regenerated from tissue culture. *J. Pl. Growth Reg.*, **14**, 135–142 [6.3.1.2; 6.3.3]
- Jourdan C. & Rey H. (1996) Modelling and simulation of the architecture and development of the oil palm (*Elaeis guineensis* Jacq.) root system with special attention to practical application. In: *Proc. 1996 PORIM Int. Palm Oil Congr. ‘Competitiveness for the 21st century’* (Ed. by D. Ariffin *et al.*), pp. 97–110, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.2.2.2; 11.2.1.1]
- Jourdan C. & Rey H. (1997a) Modelling and simulation of the architecture and development of the oil palm (*Elaeis guineensis* Jacq.) root system. 1. The model. *Pl. Soil*, **190**, 217–233 [4.5.5; 11.2.1.2; 11.2.1.3]

- Jourdan C. & Rey H. (1997b) Modelling and simulation of the architecture and development of the oil palm (*Elaeis guineensis* Jacq) root system. 2. Estimation of root parameters using the RACINES postprocessor. *Pl. Soil*, **190**, 235–246 [4.5.5; 11.2.1.2; 11.2.1.3]
- Jourdan C. & Rey H. (1997c) Architecture and development of the oil palm (*Elaeis guineensis* Jacq) root system. *Pl. Soil*, **189**, 33–48 [2.2.1.5; 11.2.1.2; 11.2.1.3]
- Jourdan C., Michaux-Ferrière N. & Perbal G. (2000) Root system architecture and gravitropism in the oil palm. *Ann. Bot.*, **85**, 861–868 [2.2.1.5]
- Julia J.F. (1979) Mise en évidence et identification des insectes responsables des maladies juveniles du cocotier et du palmier à huile en Côte d'Ivoire. *Oléagineux*, **34**, 385–393 [12.1.4]
- Julia J.F. & Mariau D. (1982) Deux espèces de *Sogatella* (Homoptera: Delphacidae) vectrices de la maladie de la pourriture sèche du coeur des jeunes cocotiers en Côte d'Ivoire. *Oléagineux*, **37**, 517–520 [12.1.5.4; 12.4]
- Jungk A. (2001) Root hairs and the acquisition of plant nutrients from soil. *J. Plant Nutr. Soil Sci.*, **164**, 121–129 [11.2.3]
- Kaepler S.M., Kaepler H.F. & Rhee Y. (2000) Epigenetic aspects of somaclonal variation in plants. *Pl. molec. Biol.*, **43**, 179–188 [6.3.1.2]
- Kalupahana A. & Mapa R.B. (1997) Land suitability evaluation for cultivation of oil palm in the wet zone of Sri Lanka. *Trop. Agric. Res.*, **9**, 245–260 [8.1.3.1]
- Kamarudin H., Ariffin D., Jalani B.S. & Mohd Nor M.Y. (1999) Pulp and paper from oil palm biomass. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 213–223, Malaysian Oil Palm Growers' Council, Kuala Lumpur [11.7.3; 13.6.1.1]
- Kamarudin N. & Basri Wahid M. (1997) Status of rhinoceros beetle, *Oryctes rhinoceros* (Coleoptera: Scarabaeidae) as a pest of young oil palm in Malaysia. *Planter, Kuala Lumpur*, **73**, 5–21 [12.2.4.1]
- Kamarudin N., Walker A.K., Basri Wahid M., Lasalle J. & Polaszek A. (1996) Hymenopterous parasitoids associated with the bagworms *Metisa plana* and *Mahasena corbetti* (Lepidoptera: Psychidae) on oil palms in Peninsular Malaysia. *Bull. ent. Res.*, **86**, 423–439 [12.2.5.2]
- Kamarudin N., Basri Wahid M., Mohd Isa Z. & Maimon Abdullah. (1999) Population studies of *Oryctes rhinoceros* in an oil palm replant using pheromone traps. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 477–496, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.4.1]
- Kamarudzaman A. (2000) Integrated FFB evacuation system: Golden Hope's approaches and experience. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 659–671, Incomp. Soc. Planters, Kuala Lumpur [10.4.5; 10.4.6]
- Kamarudzaman A. & Lani Rosdi M. (1996) Plantation mechanisation: cost and efficiency. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 294–300, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.4.6]
- Kamarudzaman A., Mohd Ali A. & Mohd Hashim T. (1994) Mechanised in-field collection of FFB for improved productivity. In: *Management for enhanced profitability in plantations* (Ed. by Chee K.H.), pp. 289–298, Incomp. Soc. Planters, Kuala Lumpur [10.4.5]
- Kanapathy K., Jorgensen H.K. & Gurmit S. (1981) Preparation and utilisation of dried palm oil mill effluent (POME). In: *Proc. Natn. Workshop 'Oil palm by-product utilisation'*, pp. 45–48, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.3.6; 13.4.8.1; 13.6.3]
- Kang S.M. (1986) Plant quarantine in the transfer of oil palm genetic materials. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 206–215, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.10]
- Kang S.M. (1999) The *Elaeidobius kamerunicus* story. *Planter, Kuala Lumpur*, **75**, 143–150 [2.2.2.5]
- Kang S.M. & Zam A.K. (1982) *Quarantine aspects of the introduction into Malaysia of an oil palm insect pollinator*. Paper presented at Int. Conf. 'Plant protection in the tropics', 1–4 Mar., Kuala Lumpur [2.2.2.5; 12.5.1]
- Kapulnik Y. (1996) Plant growth promotion by rhizosphere bacteria. In: *Plant roots – the hidden half* (Ed. by Y. Waisel, A. Eshel & U. Kafafi), pp. 769–782, Marcel Dekker, New York [11.2.3]
- Karley A.J., Leigh R.A. & Sanders D. (2000) Where do all the ions go? The cellular basis of differential ion accumulation in leaf cells. *Trends Pl. Sci.*, **5**, 465–470 [11.4.2.2]
- Kathirithamby J., Simpson S., Solulu T. & Caudwell R. (1998) *Strepsiptera parasites* – novel biocontrol tools for oil palm integrated pest management in Papua New Guinea. *Int. J. Pest Manage.*, **44**, 127–133 [12.2.5.4]
- Kawamoto H., Mohamed W.Z., Shukur N.I.M., Ali M.S.M., Ismail Y. & Oshio S. (2001) Palatability, digestibility and voluntary intake of processed oil palm fronds in cattle. *Jpn. agric. Res. Q.*, **35**, 195–200 [13.6.3]
- Kee K.K. (1995) Regional rainfall pattern and climatic limitations for plantation crops in Peninsular Malaysia. *Planter, Kuala Lumpur*, **71**, 67–78 [3.2.3; 8.1.5.4]
- Kee K.K. & Chew P.S. (1993) Oil palm responses to nitrogen and drip irrigation in a wet monsoonal climate in Peninsular Malaysia. In: *Proc. 1991 Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 321–335, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.3.2.3; 10.3]
- Kee K.K. & Chew P.S. (1996) Nutrient loss through surface runoff and soil erosion – implications for improved fertiliser efficiency in mature oil palms. In: *Proc. PORIM Int. Oil Palm Congress*, pp. 153–169, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.3.1.1; 11.6.2.6; 11.7.4.1]
- Kee K.K. & Chew P.S. (1997) Nutrients recycled from pruned fronds in mature oil palm (*Elaeis guineensis* Jacq.). In: *Plant nutrition for sustainable food production and the environment* (Ed. by T. Ando), pp. 601–602, Kluwer Academic, Dordrecht [11.1.3.1]
- Kee K.K. & Soh A.C. (2002) *Management of oil palms on slopelands in Malaysia*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [8.1.3.2]
- Kee K.K., Goh K.J., Chew P.S. & Tey S.H. (1994) An integrated site specific fertiliser recommendation system (INFERS) for high productivity in mature oil palms. In: *Management for enhanced profitability in plantations* (Ed. by Chee K.H.), pp. 83–100, Incomp. Soc. Planters, Kuala Lumpur [11.6.2.1; 11.6.2.2; 11.6.2.3; 11.6.2.4; 11.6.2.6]
- Kee K.K., Chew P.S. & Goh K.J. (1995a) Manganese deficiency in mature oil palms in Malaysia. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*),

- p. 639, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.4.1.3; 11.8.5]
- Kee K.K., Goh K.J. & Chew P.S. (1995b) Investigation into manganese deficiency in mature oil palms (*E. guineensis*) in Malaysia. *Fert. Res.*, **40**, 1–6 [11.8.5]
- Kee K.K., Goh K.J. & Chew P.S. (1995c) Effects of NK fertilisers on soil pH and exchangeable K status. In: *Plant – soil interactions at low pH* (Ed. by R.A. Date *et al.*), pp. 809–815, Kluwer Academic, Dordrecht [11.2.1.3; 11.5.1]
- Kee K.K., Chew P.S., Gan H.H. & Goh K.J. (1998) Validation of a site yield potential model for oil palms in Malaysia. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 150–163, Indonesian Oil Palm Res. Inst., Medan, Indonesia [8.1.6; 10.7.1; 10.7.2; 10.7.3]
- Kee K.K., Goh K.J. & Chew P.S. (2000) Water cycling and balance in mature oil palm agroecosystem in Malaysia. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 251–275, Incomp. Soc. Planters, Kuala Lumpur [3.2.2.1; 3.2.2.3; 3.3.1; 8.1.3.4; 11.6.2.6]
- Kellens M. (1996) Developments in fractionation technology: use of high pressure membrane filter presses in dry fractionation. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century – Chemistry and technology'* (Ed. by Badri Muhammad *et al.*), pp. 335–345, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.3.3.1]
- Kemp R. & Stratford R. (2000) *Nucleotide sequence encoding a protein with beta-glucanase activity and use thereof*. International Patent No. WO 00/01804 [6.6.2.2]
- Kerslake C.J.C. (1984) *Fingerprinting of oil palm clones*. Thesis, Univ. of Cambridge, Cambridge [6.2.1.1]
- Keys A., Anderson J.T. & Grande F. (1957) Prediction of serum-cholesterol responses of man to changes in fats in the diet. *Lancet*, **ii**, 959–966 [14.4.1]
- Khairudin H. (1990a) Results of four trials on *Ganoderma* basal stem rot of oil palm in Golden Hope estates. In: *Proc. Ganoderma Workshop* (Ed. by D. Ariffin & B.S. Jalani), pp. 113–131, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.3]
- Khairudin H. (1990b) *Basal stem rot of oil palm: incidence, etiology and control*. Thesis, Universiti Pertanian Malaysia, Selangor, Malaysia [12.1.6.3]
- Khairudin H. (1995) Basal stem rot of oil palm caused by *Ganoderma boninense*: an update. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 739–749, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.3]
- Khairudin H. & Teoh C.H. (1988) Herbicide induced parthenocarp in oil palm – preliminary screening of herbicides. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 210–214, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [2.2.2.7]
- Khairudin H., Lim T.K. & Abdul Rahman A.R. (1993) Pathogenicity of *Ganoderma boninense* Pat. on oil palm seedlings. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 418–423, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.3]
- Khalid H., Zin Z.Z., Tarmizi Mohamad A., Hamdan A.B. & Pilus Zambri M. (1996a) *Removal of pruned fronds (petioles) from oil palm plantation: effect on crop performance and nutrient value*. Paper presented at Conf. 'Sustainability of oil palm plantations – agronomic and environmental perspectives', Int. Soc. Oil Palm Agronomists, Kuala Lumpur [13.6.1]
- Khalid H., Zin Z.Z. & Anderson J.M. (1996b) Management of palm residues using various replanting techniques in oil palm plantations. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 241–253, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.2]
- Khalid H., Brookes P.C., Anderson J.M. & Zin Z.Z. (1998) Microbial biomass and soil organic matter dynamics in oil palm (*Elaeis guineensis* Jacq.) plantations, West Malaysia. *Soil Biol. Biochem.*, **30**, 547–552 [3.4.3.8; 8.3.2; 10.1.3.2; 11.7.1]
- Khalid H., Zin Z.Z. & Anderson J.M. (1999a) Quantification of oil palm biomass and nutrient value in a mature plantation. II. Below-ground biomass. *J. Oil Palm Res.*, **11**, 63–71 [8.3.2; 11.2.1.2; 11.7.1]
- Khalid H., Zin Z.Z. & Anderson J.M. (1999b) Effects of oil palm residues management at replanting on soil nutrient dynamics and oil palm growth. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 43–54, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.2]
- Khalid H., Zin Z.Z. & Anderson J.M. (1999c) Quantification of oil palm biomass and nutrient value in a mature plantation. I. Above-ground biomass. *J. Oil Palm Res.*, **11**, 23–32 [8.3.2; 11.2.1.2; 11.7.1]
- Khalid H., Zin Z.Z. & Anderson J.M. (2000) Soil nutrient dynamics and palm growth performance in relation to residue management practices following replanting of oil palm plantations. *J. Oil Palm Res.*, **12**, 25–45 [11.7.1]
- Khalid Ibrahim A. (1996) Competitiveness of the oil palm industry for the 21st century – a global perspective. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), p. ix–xi, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.4.2.1]
- Khamaruddin M. (1980) Mechanical land clearing. *Planter, Kuala Lumpur*, **56**, 559–574 [8.3.3.2]
- Khaw C.H. & Ng S.K. (1997) *Performance of commercial scale clonal oil palm (Elaeis guineensis Jacq.) planting in Malaysia*. Paper presented at Int. Soc. Hort. Sci. Symp., 29 Sept. – 3 Oct., Brisbane [6.5.3]
- Khoo K.M. (2001) Strategic thrust in addressing current challenges: the plantation perspective. *Planter, Kuala Lumpur*, **77**, 405–413 [8.3.4.1; 10.6.2]
- Khoo K.T. & Chew P.S. (1977) Effect of age of oil palm seedlings at planting out on growth and yield. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 107–114, Incomp. Soc. Planters, Kuala Lumpur [9.1.1; 9.2.1]
- King G., Lewis F.J. & Yambun J.J. (1998) Adoption of fertiliser by smallholders in West New Britain. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 606–612, Indonesian Oil Palm Res. Inst., Medan, Indonesia [10.8.1.3]
- Klun J.A., Neal J.W., Leonhardt B.A. & Schwarz M. (1986) Suppression of female bagworm, *Thyridopteryx ephemeraeformis* reproduction potential with its sex pheromone, 1-MBD. *Entomol. Exp. Applic.*, **40**, 231–238 [12.2.5.2]
- Kochu Babu M. (1988) Spear rot of oil palm (*Elaeis guineensis* Jacq.) in India. *J. Plantation Crops*, **16** (Suppl.), 281–286 [12.1.7.1]

- Kochu Babu M. & Ramachandran Nair K. (1993) Distribution of spear rot disease of oil palm (*Elaeis guineensis* Jacq.) and its possible association with MLO diseases of palms in Kerala, India. *Planter, Kuala Lumpur*, **69**, 59–66 [12.1.7.1]
- Koh M.P., Rahim S., Mohd Nor M.Y., Kamarudin H. & Jalani B.S. (1999) Manufacture of building materials from oil palm biomass. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 199–211, Malaysian Oil Palm Growers' Council, Kuala Lumpur [11.7.3; 13.6.1.2]
- Kok T.F., Goh K.J., Chew P.S., Gan H.H., Heng Y.C., Tey S.H. & Kee K.K. (2000) Advances in oil palm agronomic recommendations. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 215–232, Incomp. Soc. Planters, Kuala Lumpur [10.7.4; 11.6.2.1; 11.6.2.4; 11.6.2.6]
- Korpelainen H. (1998) Labile sex expression in plants. *Biol. Rev. Camb. Phil. Soc.*, **73**, 157–180 [4.4.4.2]
- Korytkowski C.A. & Ruiz A. (1980) The oil palm bunch miner, *Castnia daedalus* (Cramer) in the Tocachi plantation (Peru). *Oléagineux*, **35**, 1–11 [12.2.8.2]
- Kouame B. (1978) Measurements of mitochondrial activity in the oil palm (*E. guineensis* Jacq.) – demonstration of mitochondrial heterosis and comparison of the mitochondrial activity of several hybrids. *Oléagineux*, **33**, 267–275 [5.2.7]
- Kouame B. & Noiret J.M. (1982) A precocious test for productivity in the oil palm (*Elaeis guineensis* Jacq.) by measurement on mitochondrial activities. In: *Oil palm in agriculture in the eighties*, (Ed. by E. Pushparajah & Chew P.S.), pp. 33–46, Incomp. Soc. Planters, Kuala Lumpur [5.2.7]
- Koutou A., Kouame B. & d'Auzac J. (1992) Search for enzymatic markers linked to oil content in the mesocarp of oil palm (*Elaeis guineensis* Jacq.) fruits. *Oléagineux*, **47**, 155–163 [5.2.8.3]
- Kovachich W.G. (1948) A preliminary anatomical note on vascular wilt disease of the oil palm (*Elaeis guineensis*). *Ann. Bot.*, **12**, 327–329 [12.1.6.2]
- Kovachich W.G. (1954) *Cercospora elaeidis* leaf spot of the oil palm. *Trans. Br. mycol. Soc.*, **37**, 209–212 [12.1.2.1]
- Kovachich W.G. (1956a) Patch yellow disease of the oil palm. *Trans. Br. mycol. Soc.*, **39**, 427–430 [12.1.5.5]
- Kovachich W.G. (1956b) Necrotic spotting of the oil palm by *Cercospora elaeidis* Steyaert. *Trans. Br. mycol. Soc.*, **39**, 297–300 [12.1]
- Kovachich W.G. (1957) Some diseases of the oil palm in the Belgian Congo. *J. W. Afr. Inst. Oil Palm Res.*, **2**, 221–229 [12.1; 12.1.5.1]
- Kowal J.M.L. & Tinker P.B. (1959) Soil changes under a plantation established from high secondary forest. *J. W. Afr. Inst. Oil Palm Res.*, **2**, 376–389 [10.1.4; 11.7.5]
- Kularatne R.S., Shah F.H. & Rajanaidu N. (2000) *Investigation of genetic diversity in African natural oil palm populations and Deli dura using AFLP markers*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.2.8.2]
- Kuntom A. & Hamirin K. (2000) Soaps from palm products. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 1102–1140, Malaysian Palm Oil Board, Kuala Lumpur [14.3.6.1]
- Kuntom A., Dirinck P.J. & Schamp N.M. (1989) Identification of volatile compounds that contribute to the aroma of fresh palm oil and oxidized oil. *Elaeis*, **1**, 53–61 [14.3.1]
- Kuruvilla K.J. & Mohandas N.N. (1997) Challenges in large scale oil palm planting in central Kalimantan. In: *Plantation management for the 21st century* (Ed. by E. Pushparajah), pp. 91–101, Incomp. Soc. Planters, Kuala Lumpur [1.4.3.2]
- Kushairi A. & Rajanaidu N. (2000) Breeding populations, seed production and nursery management. In: *Advances in oil palm research*, Vol. I (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 39–98, Malaysian Palm Oil Board, Kuala Lumpur [5.1.1.2; 5.1.6.2; 5.2.1.1; 5.3.2; 12.1.10]
- Kushairi A., Rajanaidu N., Jalani B.S., Din M.A., Rafi M.Y. & Junaidah J. (2000) *Evaluation of Tanzania and Angola oil palm genetic collections*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.1.7.2]
- Kushairi A., Rajanaidu N. & Jalani B.S. (2001) Response of oil palm progenies to different fertiliser rates. *J. Oil Palm Res.*, **13**, 84–96 [5.5.1.7; 11.4.4.2]
- Labro M.F., Guénin G. & Rabéchault H. (1964) Essai de levée de dormance des graines de palmier à huile (*Elaeis guineensis* Jacq.) par des températures élevées. *Oléagineux*, **19**, 757–765 [7.1.1.1]
- Lafaille J.P. & Daniel M. (1965) Soins aux jeunes palmiers et remplacements. *Oléagineux*, **20**, 667–668 [9.1.5]
- Lai C.F. (2000) Mechanical fertiliser spreaders for oil palm conditions – types and costs with emphasis on the turbo-spin air-assisted fertiliser spreader. *Planter, Kuala Lumpur*, **76**, 483–492 [10.2.1; 11.9.3]
- Lamade E. (1997) A rapid method for estimating leaf area index on oil palm. *Plantations, Recherche, Développement*, **4**, 385–390 [4.1.3.1; 4.1.4.2]
- Lamade E. & Setiyo I.E. (1996a) Test of Dufrene's production model on two contrasting families of oil palm in North Sumatra. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 427–435, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.1.2; 4.1.4.3; 4.3.8]
- Lamade E. & Setiyo E. (1996b) Variation in maximum photosynthesis of oil palm in Indonesia: comparison of three morphologically contrasting clones. *Plantations, Recherche, Développement*, **3**, 429–435 [4.3.4; 4.3.8]
- Lamade E., Bonnot F. & Poeloengan Z. (1996a) Modelling photosynthesis and stomatal response of oil palm clones to environmental conditions in North Sumatra (Indonesia) – implication for plant breeding. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 87–96, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.3.8.2]
- Lamade E., Djegui N. & Leterme P. (1996b) Estimation of carbon allocation to the roots from soil respiration measurements of oil palm. *Pl. Soil*, **181**, 329–339 [4.2.1.4]
- Lamade E., Bonnot F., Pamin K. & Setiyo I.E. (1998a) Quantitative approaches of oil palm phenology in different environments for the La Mé × Deli and Yangambi materials – investigations in the inflorescences cycle process. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 287–301, Indonesian Oil Palm Res. Inst., Medan, Indonesia [4.4.8]
- Lamade E., Setiyo I.E., Muluck C. & Hakim M. (1998b) *Physiological study of three contrasting clones in Lampung (Indonesia) under drought in 1997*. Paper presented at Int. Conf.

- 'Developments in oil palm plantation industry for the 21st century', 21–22 Sept., Bali, Indonesia [5.3.6.1; 6.4.3.1]
- Lamade E., Setiyo E. & Purba A. (1998c) Gas exchange and carbon allocation of oil palm seedlings submitted to water logging in interaction with N fertiliser application. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 573–584, Indonesian Oil Palm Res. Inst., Medan, Indonesia [4.3.3.5]
- Lambourne J. (1935) Note on the root habit of oil palms. *Malay. agric. J.*, **23**, 582–583 [2.2.1.5; 11.2.1.2]
- Laranjeira F.F., Amorim L., Bergami Filho A., Berger R.D. & Hau B. (1998) Análise espacial do amarelecimento fatal do den-dezeiro como ferramenta para elucidar sua etiologia. *Fitopatol. bras.*, **23**, 397–403 [12.1.7.2]
- Last F.T. (2001) *Ecosystems of the World 19 – Tree crop ecosystems*. Elsevier Science, Amsterdam [8.4.3.2]
- Latif S. (1991) Identifikasi mikrospora kelapa sawit *Elaeis guineensis* Jacq. untuk kultur haploid. *Buletin Perkebunan*, **22**, 217–238 [6.6.1.1]
- Lauzeral A. (1980) Les sols d'Amérique latine et la culture du palmier à huile. Mise en valeur. Aménagement. Fertilisation et potentiel de production. *Oléagineux*, **35**, 477–485 [3.5.3]
- Lavelle P. (1994) Soil fauna and sustainable land use in the humid tropics. In: *Soil resilience and sustainable land use* (Ed. by D.J. Greenland & I. Szabolcs), pp. 267–280, CAB International, Wallingford [3.4.3.8]
- Lawrence M.J. & Rajanaidu N. (1986) The genetical structure of natural populations and sampling strategy. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 15–26, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.7.2]
- Lawton D.M. (1982) Pollination and fruit set in the oil palm (*Elaeis guineensis* Jacq.). In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 241–262, Incomp. Soc. Planters, Kuala Lumpur [2.2.2.2]
- Lawton J.H. & Brown V.K. (1993) Redundancy in ecosystems. In: *Biodiversity and ecosystem functioning* (Ed. by D. Schulze & H.A. Mooney), pp. 255–270, Springer, Heidelberg [8.2.1]
- Lecoustre R., Mariau D., Phillippe R. & Desmier de Chenon R. (1980) Contribution a la mise au point d'une lutte biologique contre *Coelaenomenodera*. 2. Introduction en Côte-d'Ivoire d'un hyménoptère Eulophidae du genre *Chrysonotomyia* Ashmead de Madagascar. *Oléagineux*, **35**, 177–186 [12.2.5.5]
- Lee A.K. & Kasbi H. (1980) Intercropping cocoa and oil palms. In: *Proc. Int. Conf. Cocoa and coconuts*, pp. 158–171, Incomp. Soc. Planters, Kuala Lumpur [8.4.3.3]
- Lee C.H. (1995) Rat control in cocoa and oil palms and the implications of toxicity on barn owls. *Planter, Kuala Lumpur*, **71**, 531–538 [12.3.1]
- Lee C.H. (1999) Yield potential of Golden Hope D × P oil palm planting materials. In: *Proc. 1996 Seminar 'Sourcing of oil palm planting materials for local and overseas joint ventures'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 106–117, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.3.2; 5.5.1.1]
- Lee C.H. & Donough C.R. (1993) Genotype–environment interaction in oil palm clones. In: *Proc. 1991 Int. Soc. Oil Palm Breeders Workshop 'Genotype–environment interaction studies in perennial tree crops'*, pp. 33–45, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.7; 6.4.3.1]
- Lee C.H. & Pang T.Y. (2000) *Breeding for short height increment in oil palm*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.1.1.1]
- Lee C.H. & Toh P.Y. (1991) Yield performance of Golden Hope OPRS D × P planting materials. *Planter, Kuala Lumpur*, **67**, 317–324 [5.5.2; 5.6]
- Lee C.H. & Yeow K.H. (1985) Progress in breeding and selection for seed production at HMPB Oil Palm Research Station. *Planter, Kuala Lumpur*, **61**, 18–31 [5.5.1.1]
- Lee C.H., Yong Y.Y., Ling A.H. & Law I.H. (1988) Genotype–environment interaction and yield stability studies in the oil palm. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 155–161, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.7]
- Lee C.H., Yong Y.Y., Donough C.R. & Chiu S.B. (1990) Selection progress in the Deli *dura* population. In: *Proc. Workshop 'Progress of oil palm breeding populations'*, pp. 81–89, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.1; 5.5.2.2]
- Le Guen V., Jacquemard J.C. & Kouame B. (1989) *Oil palm breeding in Cote d'Ivoire*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [5.2.7; 5.5.2.3]
- Le Guen V., Ouattara S. & Jacquemard J.C. (1990) Oil palm selection with a view to easier harvesting. Initial results. *Oléagineux*, **45**, 523–531 [5.6; 10.4.7]
- Le Guen V., Samaritana G., Zarin Othman A., Chin C.W., Konan K. & Durand-Gasselin T. (1991) Oil production in young oil palm clones. *Oléagineux*, **46**, 347–359 [6.1; 6.4.2]
- Le Guen V., Amblard P., Omore A., Koutou A. & Meunier J. (1993) The IRHO *Elaeis oleifera* × *Elaeis guineensis* interspecific hybrid programme. In: *Proc. 1991 PORIM Int. Palm Oil Conf.–Agriculture* (Ed. by Y. Basiron *et al.*), pp. 489–490, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.6]
- Lehrian D.W., Keeney P.G. & Butler D.R. (1980) Triglyceride characteristics of cocoa butter from cacao fruit matured in a microclimate of elevated temperature. *J. Amer. Oil Chem. Soc.*, **57**, 66–69 [13.1.2]
- Leigh R.A. & Wyn Jones R.G. (1984) A hypothesis relating critical potassium concentration for growth to the distribution and functions of this ion in the plant cell. *New Phytol.*, **97**, 1–13 [11.4.2.2]
- Lenfant C. & Thyron F.C. (1996) Extraction of carotenoids from palm oil II. Isolation methods. *Ol Corps Gras Lipides*, **3**, 294–307 [14.4.3]
- Lenton G.M. (1980) *Biological control of rats in oil palm by owls*. Paper presented at 5th Int. Symp. Trop. Ecology 'Tropical ecology and development', Int. Soc. Trop. Ecology, Kuala Lumpur [12.3.1]
- Lenton G.M. (1985) History, distribution and origin of barn owls *Tyto alba* in the Malay Peninsula. *Bull. Br. Ornith. Cl.*, **105** (2), 54–58 [12.3.1]
- Lepesme P. (1946) Les charançons floricoles des palmiers. *Agron. Trop.*, **1**, 400 [2.2.1.5]
- le Verdier A. & Genty P. (1988) Damage and control of *Hispoleptis subfasciata* Pic., an oil palm phyllophagous hispid, in Latin America. *Oléagineux*, **43**, 397–407 [12.2]
- Liau S.S. (1979) Insect pests of legume covers. In: *Proc. Soil microbiology and plant nutrition symposium* (Ed. by W.J. Broughton), pp. 477–479, University of Malaya, Kuala Lumpur [12.5.2]
- Liau S.S. (1985) Predators of the pollinating weevil, *Elaeidobius*

- kamerunicus* Faust (Curculionidae) in Malaysian oil palm estates. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 41–49, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.5.1]
- Liau S.S. (1990) Rat population in oil palm replants and crop loss assessment. In: *Proc. 3rd Int. Conf. 'Plant protection in the tropics'*, Vol. IV, pp. 8–18, Malaysian Plant Protection Soc., Kuala Lumpur [12.3.1]
- Liau S.S. & Ahmad Alwi (1993) The control of *Oryctes rhinoceros* by clean clearing and its effect on early yield in palm-to-palm replants. In: *Proc. 1991 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 396–403, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.4.1]
- Liau S.S. & Ahmad Alwi (1995) Defoliation and crop loss in young oil palm. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 408–427, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.2.2.1; 4.3.6.3; 4.4.6; 12.2.1.2; 12.2.4.1]
- Liaw A.M.K. (1983) Control of some mammalian pests through trapping. *Planter, Kuala Lumpur*, 59, 215–222 [12.3.2]
- Lim K.C. & Chan K.W. (1993) Comparison of Guthrie Natural Fertiliser with other slow release organic fertilisers. In: *Proc. 1991 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 370–375, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [7.2.2.3]
- Lim K.C. & Chan K.W. (1998) Bunch components studies over the past two decades. In: *Proc. 1996 Int. Conf. 'Oil and kernel production in oil palm – a global perspective'* (Ed. by N. Rajanaidu, I.E. Henson & B.S. Jalani), pp. 133–150, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.3.5.2; 4.4; 4.4.7; 4.5.2]
- Lim K.C. & Zaharah A.R. (2000) Decomposition and N and K release by oil palm empty fruit bunches applied under mature palms. *J. Oil Palm Res.*, 12, 55–62 [10.1.3.2; 11.7.2.1]
- Lim K.C., Salleh A. & Chan K.W. (1988) *Economics of utilising the Guthrie lightweight harvesting pole*. Paper presented at PORIM Natn. Conf. Oil Palm [10.4.3]
- Lim K.C., Chan K.W., Woo Y.C., Hashim M.T. & Loong S.G. (1995) The anionic effects of chloride and sulphate on growth and yield of oil palm. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 351–359, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.4.5.2]
- Lim K.H. (1983) Crude oil clarification. In: *Proc. Regional Workshop 'Palm oil mill technology and effluent treatment'*, pp. 61–84, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.3.6]
- Lim K.H. (1988) Trials on long-term effects of application of POME on soil properties, oil palm nutrition and yields. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 575–604, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.7.2.2]
- Lim K.H. (1990) Soil erosion control under mature oil palms on slopes. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 191–198, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.4.3.8; 8.1.3.6]
- Lim K.H. & Ho C.Y. (1993) Irrigation trials in oil palm nurseries. In: *Proc. 1991 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 211–218, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [7.2.2.3]
- Lim K.H. & Silek B. (2001) Termite infestation on oil palms planted on deep peat in Sarawak: Tradewinds experience. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 355–368, Malaysian Palm Oil Board, Kuala Lumpur [12.2]
- Lim K.H. & Toh P.Y. (1985) The accuracy and precision of bunch analysis. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 91–109, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2.4.2]
- Lim K.H., Chuah J.H. & Ho C.Y. (1994) Improving water management practices on oil palm through the water balance concept. In: *'Management for enhanced profitability in plantations'* (Ed. by Chee K.H.), pp. 101–119, Incomp. Soc. Planters, Kuala Lumpur [3.2.2.1; 3.2.2.2; 8.2.3; 10.3; 10.3.1.1; 10.3.2.1; 10.3.3]
- Lim K.H., Chuah J.H. & Ho C.Y. (1995) Effects of soil heaping on *Ganoderma* infected oil palms. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 477–486, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.1.6.3]
- Lim K.H., Mohd Hashim T., Zin Z.Z., Gurmit S. & Lim C.H. (1999) Land application of palm oil mill effluent. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 153–169, Malaysian Oil Palm Growers' Council, Kuala Lumpur [10.2.1; 11.7.2.2]
- Lim K.N., Chee C.F., Ho C.Y., Seeveneserajah K., Ratnam S. & Mau J.J. (1995) Mulching immature oil palms with oil palm trunk chippings. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 555–561, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [9.1.4.1; 9.4.2]
- Lim L.L., Yong Y.Y. & Leong T.T. (1999) *IOI's oil palm tissue culture experience*. Paper presented at 1999 PORIM Int. Palm Oil Congr., Kuala Lumpur [6.2.1.1]
- Ling A.H. (1979) Some lysimetric measurements of evapotranspiration of oil palm in central Peninsular Malaysia. In: *Proc. Symp. 'Water in agriculture in Malaysia'* (Ed. by E. Pushparajah), pp. 89–101, Malaysian Soc. Soil Sci., Kuala Lumpur [3.2.2.1; 10.3.1.1]
- Ling A.H. & Pillai G.G. (2001) Sustaining the dynamic growth of the East Malaysian palm oil industry: addressing the constraints. *Planter, Kuala Lumpur*, 77, 461–468 [1.4.3.2]
- Lo K.K. & Goh K.H. (1973) The analysis of experiments on the economics of fertiliser application on oil palms. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 338–359, Incomp. Soc. Planters, Kuala Lumpur [11.3.1]
- Lo K.K., Chan K.W., Goh K.H. & Hardon J.J. (1973) Effect of manuring on yield, vegetative growth and leaf nutrient level of the oil palm. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 324–337, Incomp. Soc. Planters, Kuala Lumpur [4.3.2]
- Loaiza Granda C. (1998) El cultivo de la palma de aceite en el Ecuador. *Palmas (Bogota)*, 19 (Special no.), 93–95 [1.4.3.11]
- Locke T. (1972) *A study of vascular wilt disease of oil palm seedlings*. Thesis, Univ. of Manchester, Manchester [12.1.6.2]
- Locke T. & Colhoun J. (1973) *Fusarium oxysporum* f.sp. *elaeidis* as a seed-borne pathogen. *Trans. Br. Mycol. Soc.*, 60, 594–596 [7.1.5; 12.1.6.2]
- Locke T. & Colhoun J. (1974) Contributions to a method of testing oil palm seedlings for resistance to *Fusarium oxysporum* Schl. f.sp. *elaeidis* Toovey. *Phytopath. Z.*, 79, 77–92 [12.1.6.2]
- Loh C.F. (1977) Preliminary evaluation of some systemic fungicides for *Ganoderma* control and phytotoxicity to oil palm. In: *International developments in oil palm* (Ed. by D.A. Earp & W.

- Newall), pp. 555–564, Incomp. Soc. Planters, Kuala Lumpur [12.1.6.3]
- Loh C.F. & Rajaratnam J.A. (1977) Replanting methods and *Ganoderma* disease in inland soil. *Malay. agric. Res. Dev. Inst. Res. Bull.*, 5, 50–53 [12.1.6.3]
- Loh H.P. & Sharma M. (1999a) The essentials of oil palm replanting: United Plantations experience. *Planter, Kuala Lumpur*, 75, 289–303 [8.3.2]
- Loh H.P. & Sharma M. (1999b) *Short-term yield forecasting using Ulu Bernam method*. Paper presented at Symp. 'Yield potential and forecasting', 4–5 Dec., Subang Jaya, Malaysia, [4.5.4]
- Loncin M. & Jacobsberg B. (1963) Studies on Congo palm oil. *J. Amer. Oil Chem. Soc.*, 40, 18–45 [13.1.2; 13.1.3]
- Loncin M. & Jacobsberg B. (1964) *Study on palm kernel acidification during storage*. Paper presented at Int. Soc. Fat Res. Congr., Hamburg [13.4.6.3]
- Loncin M. & Jacobsberg B. (1965) *Research on palm oil in Belgium and the Congo*. Paper presented at Oil Palm Conf., Tropical Products Inst., London. [13.1.2]
- Loong S.G., Nazeem M. & Letchumanan A. (1988) Optimising the use of EFB mulch on oil palms on two different soils. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 605–639, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [9.1.4.1; 10.1.3.2]
- Loong S.G., Nazeem M., Letchumanan A. & Wood B.J. (1990) Underplanting as a means to shorten the non-productive period of oil palm. In: *Proc. 1989 Int. Palm Oil Dev. Conf. Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 159–168, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.4.3]
- Lopez G., Genty P. & Ollagnier M. (1975) Contrôle préventif de la 'marchitez sorpesiva' de l'*Elaeis guineensis* en Amérique latine. *Oléagineux*, 30, 243–250 [12.1.6.4]
- Lord S., Hoare M.K. & Thompson N.M. (2002) *Composting for zero discharge – NBPOL's solution*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [10.1.3.2]
- Lortie R. (1997) Enzyme catalyzed esterification. *Biotech. Adv.*, 15, 1–15 [13.3.3]
- Lubis A.U. (1990) History and origin of oil palm breeding materials used in Marihat Research Centre. In: *Proc. Workshop 'Progress of oil palm breeding populations'*, pp. 103–119, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.3; 5.1.6.2; 5.4.6.2]
- Lubis A.U. & Adiwiganda R. (1996) Agronomic management practices of oil palm plantation in Indonesia based on land conditions. *Proc. ISOPA/IOPRI Seminar 'Agronomic update in oil palm management'*, pp. 29–62, Indon. Oil Palm Res. Inst. [3.3.1; 3.4.1.3; 3.5.1.2]
- Lubis A.U. & Daswir (1996) Progress of oil palm industry in the last ten years in Indonesia. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 391–399, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.4.3.1]
- Lubis R.A., Akiyat & Nouy B. (1990) Oil palm seed production strategy at Marihat Research Centre, Indonesia. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 56–65, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.2; 5.4.5.2]
- Lubis S., Dja'afar & Daswir (1993) The role of farmer group in increasing the income of farmer in oil palm nucleus estates in Indonesia – a case study. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 226–231, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.4.3.1; 10.8.1.2]
- Lukman Fadli M. & Poeloengan Z. (1996) Application of remote sensing technique for oil palm plantation management. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 460–467, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.7.5]
- Lukman Fadli M. & Siahaan M.M. (1995) Nutrient status and phytosanitary condition study for oil palm by using remote sensing technology. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 567–571, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.4.1.4]
- Lynch J. & Nielsen K.L. (1996) Simulation of root system architecture. In: *Plant roots – the hidden half* (Ed. by Y. Waisel, A. Eshel & U. Kafkafi), pp. 247–257, Marcel Dekker, New York [11.2.1.2]
- Ma A.N. (1999a) Treatment of palm oil mill effluent. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 113–123, Malaysian Oil Palm Growers' Council, Kuala Lumpur [1.4.3.2; 11.7.2.2; 13.4.1; 13.4.8.1; 13.4.8.2]
- Ma A.N. (1999b) Innovations in management of palm oil mill effluent. *Planter, Kuala Lumpur*, 75, 381–389 [11.6.1.1; 11.7.2.2]
- Maarsen J.W. (1985) Edible end uses of coconut and palm kernel oils. In: *'Palm kernel and coconut oils', Symp. Proc. No. 32*, pp. 53–60, British Food Manufacturing Industries Assoc., Leatherhead [14.3.4; 14.3.5]
- Maas J.G.J.A. (1923) Voorlopige mededeelingen over de selectie bij den oliepalm. *Verslag van de Derde Vergadering van de Vereniging van Proefstation-personeel*, II, 51–81 [5.1.1.1]
- McCree K.J. (1982) Maintenance requirements of white clover at high and low growth rates. *Crop Sci.*, 22, 345–351 [4.3.1.2]
- Macfarlane M., Alaka B. & Macfarlane N. (1975) Analysis of the mesocarp oils from several different oil palm hybrids. *Oil Palm News*, 20, 1 [5.3.7.1]
- McMorrow J.M. (2001) Linear regression modelling for the estimation of oil palm age from Landsat TM. *Int. J. Remote Sensing*, 22, 2243–2264 [10.7.5]
- McMorrow J.M. & Tey S.H. (2000) The potential of Landsat TM remote sensing images for oil palm estate management. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 769–791, Incomp. Soc. Planters, Kuala Lumpur [10.7.5]
- Macrae S.G. & Burnham C.P. (1981) *Land evaluation*. Oxford Science Publications, Clarendon Press, Oxford [8.1.5.3]
- Maene L.M. & Chong C.P. (1979) Drop size distribution and erosivity of tropical rainstorms under the oil palm canopy. In: *Res. Rep. Soil Sci. Dept, 1977–78*, pp. 81–93, Univ. Pertanian Malaysia, Serdang [8.1.3.6]
- Maene L.M., Thong K.C., Ong T.S. & Mokhtaruddin A.M. (1979) Surface wash under mature oil palm. In: *Proc. Symp. 'Water in agriculture in Malaysia'* (Ed. by E. Pushparajah), pp. 204–216, Malaysian Soc. Soil Sci., Kuala Lumpur [3.4.3.8; 8.1.3.6; 10.3.1.1; 11.6.2.6; 11.7.4.1]
- Mahbob Abdullah. (2001) Are companies training their planters? *Planter, Kuala Lumpur*, 77, 663–666 [10.4.6]
- Maهران A.B. & Zarin Othman A. (1999) Felda's experience in clonal oil palm planting on inland soils. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 330–350, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.4.2]

- Maheran A.B., Abu Zarin O., Aw K.T. & Chin C.W. (1995) FELDA's early experiences with vegetative propagation of the oil palm (*Elaeis guineensis* Jacq.). In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 99–113, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.1.1]
- Mahmud A.W. (2000) Mechanisation, where are we? *Planter, Kuala Lumpur*, **76**, 453–456 [10.4.7]
- Maillard G., Daniel C. & Ochs R. (1974) Analyse des effets de la sécheresse sur le palmier à huile. *Oléagineux*, **29**, 397–404 [5.3.6.1]
- Malaguti G. (1953) Pudricion del cogollo de la palmera de aceite Africana (*Elaeis guineensis* Jacq.) en Venezuela. *Agronomia Trop.*, **3**, 13–31 [12.1.6.6; 12.1.9]
- Malaurie B. (1987) L'embryogenèse somatique en milieu liquide du palmier à huile: *Elaeis guineensis* Jacq. et *E. guineensis* × *E. melanococca*. Premiers résultats. *Oléagineux*, **42**, 217–222 [5.5.1.6; 6.5.1.1]
- Malek M. & Barlow C. (1988) The production structure of the Malaysian oil palm industry with special reference to the smallholder sector. *Palm Oil Res. Inst. Malaysia, Occ. Paper*, **24**, 1–54 [10.8.1]
- Malek M. & Mohd Nasir A. (1995) Wage, cost and productivity in oil palm estates. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 212–220, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.4.4.1]
- Malek M. & Yaakob Hitam (1989) Harvesting and mechanised in-field collection of FFB. *Planter, Kuala Lumpur*, **65**, 554–562 [10.4.5]
- Maley J. (1999) L'expansion du palmier à huile (*Elaeis guineensis*) en Afrique Centrale au cours des trois derniers millénaires: nouvelles données et interprétations. In: *L'homme et la forêt tropicale* (Ed. by S. Bahuchet *et al.*), pp. 237–254, Travaux Société d'Ecologie Humaine, Marseilles [1.1.1]
- Maley J. & Chepstow-Lusty A. (2001) *Elaeis guineensis* Jacq. (oil palm) fluctuations in central Africa during the late Holocene: climate or human driving forces for this pioneering species? *Vég. Hist. Archaeobotany*, **10**, 117–120 [1.1.1]
- Maliphant G.K. (1978) The optimum spacing for oil palms in Nigeria. *J. Nigerian Inst. Oil Palm Res.*, **5**, 67–78 [9.3.3.3]
- Mann P.S., Hoare M.K., Wilson R., Dickson I.A., Thompson N.M. & Lord S. (2002) *Integration of beef cattle with oil palm: NBPOL's commercial experience*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [8.4.3.4]
- Margeson M.A. & Schwartz A.J. (1993) Synthetic lubricants – an application for oleochemicals. In: *Proc. Int. Oil Palm Conf. – Chemistry and technology* (Ed. by Y. Basiron *et al.*), pp. 193–198, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.3.6.1]
- Maria M., Clyde M.M. & Cheah S.C. (1995) Cytological analysis of *Elaeis guineensis* (*tenera*) chromosomes. *Elaeis*, **7**, 122–134 [2.2.1.6]
- Maria M., Clyde M.M. & Cheah S.C. (1998) Cytological analysis of *Elaeis guineensis* and *Elaeis oleifera* chromosomes. *J. Oil Palm Res.*, **10** (1), 68–91 [2.2.1.6]
- Mariana M.N. (1999) Environment quality act. In: *Oil palm and the environment – a Malaysian perspective* (Ed. by Gurmit Singh *et al.*), pp. 261–264, Malaysian Oil Palm Growers' Council, Kuala Lumpur [8.3.2; 13.4.8.1; 13.4.8.2]
- Mariau D. (1968) Méthodes de lutte contre le Rhynchophore. *Oléagineux*, **23**, 443–446 [12.2.6.1]
- Mariau D. (1976a) Insect pests in West Africa. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 369–383, Elsevier, Amsterdam [12.2.1.1; 12.2.5.5]
- Mariau D. (1976b) Insect pests in South America. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 385–393, Elsevier, Amsterdam [12.2; 12.2.4.2; 12.2.8.3]
- Mariau D. (1993) Insecticides recommended against oil palm and coconut pests. *Oléagineux*, **48**, 530–532 [12.2]
- Mariau D. (1994) Phytosanitary monitoring of oil palm and coconut plantations. *Oléagineux*, **49**, 250–254 [12.2.1.3]
- Mariau D. (1999a) Chrysomelidae Coleoptera living off oil palm and coconut, and their parasitoids. *Ann. Soc. Entomol. Fr.*, **35**, 230–237 [12.2]
- Mariau D. (1999b) Knowledge of oil palm pests and population management. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 129–138, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.1.3; 12.2.1.4]
- Mariau D. & Bescombes J.P. (1972) Méthode de contrôle des niveaux de population de *Coelaenomenodera elaeidis*. *Oléagineux*, **27**, 425–427 [12.2.5.5]
- Mariau D. & Djib Bikoi J. (1990) *Monolepta apicicornis* Thomson (Coleoptera Chrysomelidae) oil palm root miner in West Africa. Initial results. *Oléagineux*, **45**, 311–317 [12.2]
- Mariau D. & Huguenot R. (1983) Méthode d'estimation des populations de *Castnia daedalus* (Lepidoptere Castniidae) sur le palmier à huile. *Oléagineux*, **38**, 227–230 [12.2.8.2]
- Mariau D. & Julia J.F. (1973) Les ravageurs et maladies du palmier à huile et du cocotier. *Les Parasa. Oléagineux*, **28**, 129–131 [12.2.5.1]
- Mariau D. & Morin J.P. (1971) Les ravageurs et maladies du palmier à huile et du cocotier. La Pyrale du palmier à huile. *Oléagineux*, **26**, 379–381 [12.2.3.1]
- Mariau D. & Morin J.P. (1974) La biologie de *Coelaenomenodera elaeidis* Mlk. VI. La mortalité naturelle des larves. *Oléagineux*, **29**, 549–555 [12.2.5.5]
- Mariau D., Philippe R. & Lecoustre R. (1978) Les parasites larvaires de *Coelaenomenodera elaeidis* Mlk., hispines du palmier à huile en Afrique occidentale. Introduction à une méthode de lutte biologique. *Oléagineux*, **33**, 153–160 [12.2.5.5]
- Mariau D., Desmier de Chenon R., Julia J.F. & Philippe R. (1981) Les ravageurs du palmier à huile et du cocotier en Afrique occidentale. *Oléagineux*, **36**, 168–228 [12.2; 12.2.4.3; 12.2.5.1]
- Mariau D., Desmier de Chenon R. & Sudharto P.S. (1991) Oil palm insect pests and their enemies in South east Asia. *Oléagineux*, **46**, 400–476 [12.2; 12.2.1.1; 12.2.5.1; 12.2.5.3]
- Mariau D., Renoux J. & Desmier de Chenon R. (1992) *Coptotermes curvignathus* Holmgren Rhinotermitidae, main pest of coconut planted on peat in Sumatra. *Oléagineux*, **47**, 561–568 [12.2]
- Marita J.M., Rodriguez J.M. & Nienhuis J. (2000) Development of an algorithm identifying maximally diverse core collections. *Genet. Resource Crop Evol.*, **47**, 515–526 [5.1.7.5]
- Marmey P., Besse I. & Verdeil J.L. (1991) A proteic marker found to differentiate 2 types of calli of the same clones of oil palm. *C. R. Acad. Sci., Paris, Ser.III*, **313**, 333–338 [6.3.3]
- Marschner H. (1995) *Mineral nutrition of higher plants*, 2nd edn, Academic Press, London [11]
- Marschner H., Kirkby E.A. & Engels C. (1997) Importance of cycling and recycling of mineral nutrients within plants for growth and development. *Bot. Acta*, **110**, 265–273 [11.1.2]
- Martin G. (1970) Le dessèchement des feuilles. Maladi du

- palmier à huile dans la région du Nord-Santander de Colombie. *Oléagineux*, **26**, 22–24 [12.1.6.4]
- Martínez L. (1988) La 'mancha anular' de la palma africana en Tumaco. Internal report, Federación Nacional de Cultivadores de Palma Africana, Tumaco, Colombia [12.1.5.4]
- Martoyo K. & Purba P. (1995) The utilisation of tidal swampy land for oil palm planting in Indonesia. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 562–566, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.6]
- Masani Mat Yunus A., Ho C.L. & Parveez G.K.A. (2001) Construction of PHB gene expression vectors for the production of biodegradable plastics in transgenic oil palm. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 694–711, Malaysian Palm Oil Board, Kuala Lumpur [6.6.3]
- Mathews J. & Leong T.T. (2000) Performance of two new legume species in oil palm planting. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 325–339, Incomp. Soc. Planters, Kuala Lumpur [10.1.2.3]
- Matthes M., Singh R., Cheah S.C. & Karp A. (2001) Variation in oil palm (*Elaeis guineensis* Jacq.) tissue culture-derived regenerants revealed by AFLPs with methylation-sensitive enzymes. *Theor. appl. Genet.*, **102**, 971–979 [6.3.1.2]
- Maycock J.H. (1990) Innovations in palm oil mill processing and refining. In: *Proc. Symp. 'New developments in palm oil'* (Ed. by K.G. Berger), pp. 23–37, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.1; 13.4.2; 13.4.3; 13.4.6.3; 13.5; 13.5.1]
- Maycock J.H. & Henson I.E. (1992) An instrument tower for micrometeorological measurements over oil palm. *PORIM Eng. News*, **26**, 4–8 [4.1.4.3]
- Mayes S. (1995) *The application of biotechnology toward the genetic improvement of oil palm*. Thesis, Open Univ. [5.1.7.5; 5.2.8.2; 5.4.3]
- Mayes S., James C.M., Pluhar V., Batty N.P., Jack P.L. & Corley R.H.V. (1995) The application of biotechnology to oil palm – potentials and progress. In: *Recent developments in oil palm tissue culture and biotechnology*, (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 171–189, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.2.1.1]
- Mayes S., James C.M., Horner S.F., Jack P.L. & Corley R.H.V. (1996) The application of restriction fragment length polymorphism for the genetic fingerprinting of oil palm (*Elaeis guineensis* Jacq.). *Molec. Breed.*, **2**, 175–180 [5.2.8.2; 6.2.1.1]
- Mayes S., Jack P.L., Marshall D. & Corley R.H.V. (1997) Construction of a RFLP genetic linkage map for oil palm (*Elaeis guineensis* Jacq.). *Genome*, **40**, 116–122 [5.2.8.3]
- Mayes S., Jack P.L. & Corley R.H.V. (2000) The use of molecular markers to investigate the genetic structure of an oil palm breeding programme. *Heredity*, **85**, 288–293 [5.2.8.2; 5.5.1.2]
- Mena Tascon E. & Martínez-López G. (1977) Identificación del insecto vector de la marchitez de la palma africana (*Elaeis guineensis* Jacq.). *Fitopatología Colombiana*, **6**, 2–14 [12.1.6.4]
- Mena Tascon E., Cardona Mejía C., Martínez-López G. & Dario Jimenez O. (1975) Efecto del uso de insecticidas y control de malezas en la incidencia de la marchitez sorpresiva de la palma africana (*Elaeis guineensis*, Jacq.). *Rev. Colombian Entomol.*, **1**, 1 [12.1.6.4]
- Mendez I.A.A. (2000) *Manejo integrado de la Pestalotiopsis en una plantación comercial de palma de aceite*. Paper presented at Conf. 'Competitividad y prospectiva de la palma de aceite', 6–8 Sept., Cartagena, Colombia [12.1.5.2]
- Mendham N.J. (1971) Note on leaf area measurement in oil palms. *Papua New Guinea Agric. J.*, **22**, 230–231 [4.1.3.1; 4.1.3.5]
- Menendez T. (1966) Plant physiology division. In: *2nd Annu. Rep., Nigerian Inst. Oil Palm Res.*, pp. 97–99, Benin City [7.1.1.1]
- Menendez T. (1988) The results of oil palm thinning experiments in West New Britain. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 410–418, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [9.3.6.2]
- Menendez T. & Blaak G. (1964) Plant breeding division. In: *12th Annu. Rep. W. Afr. Inst. Oil Palm Res.*, pp. 49–75, Benin City [5.3.3.1]
- Mengel K. & Kirkby E.A. (1996) *Principles of plant nutrition*. Kluwer Acad. Publ. [11.1.1]
- Menon N.R. (2000) Factors affecting oil and kernel extraction rates. In: *Advances in oil palm research*, Vol. I (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 697–743, Malaysian Palm Oil Board, Kuala Lumpur [10.5.2; 13.4.5.3]
- Menon N.R. (2001) Advances in milling technology: evolutionary changes. In: *Strategic directions for the sustainability of the oil palm industry* (Ed. by E. Pushparajah), pp. 1–19, Incomp. Soc. Planters, Kuala Lumpur [13.4.3; 13.4.3.2; 13.4.3.7]
- Mepsted R., Flood J. & Cooper R.M. (1988) *Biocontrol of Fusarium wilt of oil palm by an avirulent isolate*. Paper presented at Conf. Brit. Soc. Plant Pathol. 'Novel and unusual methods of disease control', 13–15 Dec., Reading [12.1.6.2]
- Mepsted R., Nyanduza C., Flood J. & Cooper R.M. (1991) A non-destructive quantitative method for the assessment of infection of oil palms by *Fusarium oxysporum* f.sp. *elaeidis*. *Elaeis*, **3**, 329–335 [12.1.6.2]
- Mepsted R., Flood J., Paul T. & Cooper R.M. (1994) Virulence and aggressiveness in *Fusarium oxysporum* f.sp. *elaeidis*; implications for screening for disease resistance. *Oléagineux*, **49**, 209–212 [12.1.6.2]
- Mepsted R., Flood J. & Cooper R.M. (1995a) *Fusarium wilt of oil palm I. Possible causes of stunting*. *Physiol. Molec. Pl. Pathol.*, **46**, 361–372 [12.1.6.2]
- Mepsted R., Flood J. & Cooper R.M. (1995b) *Fusarium wilt of oil palm II. Stunting as a mechanism to reduce water stress*. *Physiol. Molec. Pl. Pathol.*, **46**, 373–387 [12.1.6.2]
- Mepsted R., Flood J., Paul T., Airede C. & Cooper R.M. (1995c) A model system for rapid selection for resistance and investigation of resistance mechanisms in *Fusarium wilt of oil palm*. *Pl. Pathol.*, **44**, 749–755 [12.1.6.2]
- Mesa Dishington J. (1998) A competitive oil palm development model for Colombia. *Palmas (Bogotá)*, **19** (Special no.), 18–28 [1.4.3.9]
- Meunier J. (1969) Etude des populations naturelles d'*Elaeis guineensis* en Côte d'Ivoire. *Oléagineux*, **24**, 195–201 [5.1.7.1; 5.1.7.2; 5.1.7.4]
- Meunier J. (1975) Le 'palmier à huile' américain *Elaeis melanococca*. *Oléagineux*, **30**, 51–62 [2.3.1; 2.3.2; 5.1.7.3]
- Meunier J. (1989) *Advances in oil palm breeding – progress and prospects*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [5.4.2.2]

- Meunier J. (1995) Biotechnologies: what prospects for tropical tree crops? *Plantations, Recherche, Développement*, **2** (1), 7–18 [1.4.2.4]
- Meunier J. & Boutin D. (1975) L'*Elaeis melanococca* et l'hybride *Elaeis melanococca* × *Elaeis guineensis* – premières données. *Oléagineux*, **30**, 5–8 [5.3.7.1; 5.5.1.6]
- Meunier J. & Gascon J.P. (1972) Le schéma général d'amélioration du palmier à huile à l'IRHO. *Oléagineux*, **40**, 365–372 [5.4.2.1]
- Meunier J. & Jacquemard J.C. (1990) Improvement of the basic oil palm population at IRHO. In: *Proc. Workshop 'Progress of oil palm breeding populations'*, pp. 1–4, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.1]
- Meunier J., Gascon J.P. & Noiret J.M. (1970) Hérité des caractéristiques du régime d'*Elaeis guineensis* Jacq. en Côte d'Ivoire. *Oléagineux*, **25**, 377–382 [5.3.3.1; 5.3.3.2]
- Meunier J., Vallejo G. & Boutin D. (1976) L'hybride *E. melanococca* × *E. guineensis* et son amélioration. Un nouvel avenir pour le palmier à huile. *Oléagineux*, **31**, 519–528 [5.3.7.1; 5.3.7.3]
- Meunier J., Renard J.L. & Quillec G. (1979) Heredity of resistance to *Fusarium* wilt in the oil palm *Elaeis guineensis* Jacq. *Oléagineux*, **34**, 555–561 [5.3.5]
- Meunier J., Potier F., Amblard P. & Taillez B. (1989) Relationship between oil production and the number of bunches in oil palm (*Elaeis guineensis* Jacq.). Consequences for pollination in young plantations. *Oléagineux*, **44**, 269–279 [5.5.2.3]
- Meunier J., Baudouin L., Nouy B. & Noiret J.M. (1990) The expected value of oil palm clones. *Oléagineux*, **43**, 195–200 [6.4.1]
- Mezón R.G. & Chinchilla C.M. (1993) An inventory of the oil palm pests and their natural enemies in Central America. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 443–450, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2]
- Mezón R.G., Chinchilla C.M. & Salamanca D. (1996) The biology of *Sibine megalomorphes* Walker (Lepidoptera, Limacodidae): observations of the pest in oil palm in Costa Rica. *ASD Oil Palm Papers*, **12**, 1–10 [12.2.5.1]
- Meynadier G., Amargier A. & Genty P. (1977) Une virose de type denoncléose chez le lépidoptère *Sibine fusca* Stoll. *Oléagineux*, **32**, 357–361 [12.2.5.1]
- Mielke S. (1998) The outstanding role of Indonesia in the phenomenal development of the World palm oil industry in the past and the future. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 37–54, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.4.1; 1.4.2; 1.4.3.1]
- Mielke T. (2000) The future World demand for and prices of vegetable oils. In: *Plantation tree crops in the new Millenium: the way ahead*, (Ed. by E. Pushparajah), pp. 83–85, Incorp. Soc. Planters, Kuala Lumpur [1.4.1]
- Mielke S. (2001) *Can production of oils and fats keep pace with future consumption?* Paper presented at ISF Int. Congr., Berlin, 20 Sept [1.4.1; 1.4.2.2; 15.3.2]
- Miller R.N.G., Holderness M., Bridge P.D., Chung G.F. & Zakaria M.H. (1999) Genetic diversity of *Ganoderma* in oil palm plantings. *Pl. Pathol.*, **48**, 595–603 [12.1.6.3]
- Miller R.N.G., Holderness M. & Bridge P.D. (2000) Molecular and morphological characterization of *Ganoderma* in oil palm plantings. In: *Ganoderma diseases of perennial crops* (Ed. by J. Flood, P.D. Bridge & M. Holderness), pp. 159–182, CABI Publishing, Wallingford [12.1.6.3]
- Miranda Santos M.d., Barcelos E. & Nascimento J.C. (1986) Genetic resources of *Elaeis oleifera* (H.B.K.) Cortes in the Brazilian Amazon. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 95–101, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.7.3]
- Mite F., Carrillo M. & Espinosa J. (2000) *Influencia de la fertilización y el riego sobre el desarrollo, nutrición y rendimiento de la palma africana en la zona de Quevedo*. Paper presented at Conf. 'Competitividad y prospectiva de la palma de aceite', 6–8 Sept., Cartagena, Colombia [3.3.1; 4.1.4.3; 4.4.4.1; 10.3]
- Miyawaki Y. (1998) Major contribution of crude palm oil and palm kernel oil in the oleochemical industry. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 72–79, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.6.3.1; 13.4.7; 14.3.6.1]
- Moawad A. & Vlek P.L.G. (1998) Potential contribution of (vesicular-) arbuscular mycorrhiza to nutrient efficient crops. In: *Proc. BTIG Workshop Oil palm improvement through biotechnology*, (Ed. by J.S. Tahardi *et al.*), pp. 48–58, Biotechnology Research Unit for Estate Crops, Bogor, Indonesia [11.2.2]
- Mohd Arif S. & Mohd Nasir A. (1997) Milling cost of oil palm fresh fruit bunches: a medium term scenario. *Palm Oil Res. Inst. Malaysia, Bull.*, **35**, 1–11 [13.4.5.3]
- Mohd Jaaffar & Jalani B.S. (1999) The oil palm in Malaysia in the next millennium. *Trop. Agric. Assoc. Newslett.*, **19** (3), 9–13 [1.4.3.2]
- Mok C.K. (1966) The preparation, storage and germination of oil palm seed – conditions and practices currently believed optimal. *Chemara Research Station (Oil Palm Division), Seed Production Advisory Leaflet* [7.1.4.1]
- Mok C.K. (1970) Effect of methyl bromide fumigation on oil palm (*Elaeis guineensis* Jacq.) seed. *Proc. Int. Seed Test. Assoc.*, **35**, 243–255 [7.1.5]
- Mok C.K. (1972a) Sample size for moisture and viability testing of oil palm (*Elaeis guineensis* Jacq.) seed. *Proc. Int. Seed Test. Assoc.*, **37**, 751–761 [7.1.3.1]
- Mok C.K. (1972b) The tetrazolium test for evaluating the viability of oil palm (*Elaeis guineensis* Jacq.) seed. *Proc. Int. Seed Test. Assoc.*, **37**, 771–780 [7.1.3.1]
- Mok C.K. (1982) Heat requirement for breaking dormancy of oil palm seeds after storage under different conditions. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 197–206, Incorp. Soc. Planters, Kuala Lumpur [7.1.3.2]
- Mok C.K. & Hor Y.L. (1977) The storage of oil palm (*Elaeis guineensis*) seed after high temperature treatment. *Seed Sci. Technol.*, **5**, 499–508 [7.1.3.2]
- Mollegaard M. (1970) The effect of drying of oil palm nuts in respect of crackability of same and estimation of the percentage of shell and kernel to fruit. *Oléagineux*, **25**, 139–143 [5.2.4.2]
- Moncalvo J.M. (2000) Systematics of *Ganoderma*. In: *Ganoderma diseases of perennial crops*, (Ed. by J. Flood, P.D. Bridge & M. Holderness), pp. 23–45, CABI Publishing, Wallingford [12.1.6.3]
- Monge J.E., Vasquez N. & Chinchilla C.M. (1994) Common spear rot/crown disease in oil palm (*Elaeis guineensis* Jacq.): anatomy of the affected tissue. *Elaeis*, **6**, 102–108 [12.1.5.1]

- Monteith J.L. (1977) Climate and the efficiency of crop production in Britain. *Phil. Trans. Roy. Soc. Lond., B*, **281**, 277–294 [4.1.1.2]
- Monteith J.L. (1981) Evaporation and surface temperature. *Q. J. Roy. Meteorol. Soc.*, **107**, 1–27 [3.2.2.1]
- Morales F.J., Lozano I., Sedano R., Castano M. & Arroyave J. (2002) Partial characterization of a potyvirus infecting African oil palm in South America. *J. Phytopathol.* **150**, 297–301 [12.1]
- Morcillo F., Aberlenc-Bertossi F., Hamon S. & Duval Y. (1998) Accumulation of storage protein and 7S globulins during zygotic and somatic embryo development in *Elaeis guineensis*. *Pl. Physiol. Biochem.*, **36**, 509–514 [6.2.3]
- Morcillo F., Aberlenc-Bertossi F., Noirot M., Hamon S. & Duval Y. (1999) Differential effects of glutamine and arginine on 7S globulin accumulation during the maturation of oil palm somatic embryos. *Pl. Cell Rep.*, **18**, 868–872 [6.2.3]
- Moretzsohn M.C., Ferreira M.A., Amaral Z.P.S., Coelho P.J.A., Grattapaglia D. & Ferreira M.E. (2002) Genetic diversity of Brazilian oil palm (*Elaeis oleifera* HBK) germplasm collected in the Amazon Forest. *Euphytica*, **124**, 35–45 [5.1.7.3; 5.2.8.2]
- Moretzsohn M.C., Nunes C.D.M., Ferreira M.E. & Grattapaglia D. (2000) RAPD linkage mapping of the shell thickness locus in oil palm (*Elaeis guineensis* Jacq.). *Theor. appl. Genet.*, **100**, 63–70 [5.2.8.3]
- Morgan R.G.C., Morgan D.D.V. & Finney H.J. (1984) A predictive model for the assessment of soil erosion risk. *J. Agric. Engng Res.*, **30**, 245–253 [11.6.2.4]
- Morin J.P. & Mariau D. (1974) La biologie de *Coelaenomenodera elaeidis* Mlk. V. La mortalité au niveau des oeufs. *Oléagineux*, **29**, 233–238 [12.2.5.5]
- Morton A.G. (1942) *A study of the relationship between growth and mycorrhizal development in the oil palm*. Internal Report, Lever Bros & Unilever [2.2.1.5; 11.2.2]
- Moura J.I.L., Mariau D. & Delabie J.H.C. (1993) Efficacité de *Paratheresia menezesi* Townsend (Diptera: Tachinidae) pour le contrôle biologique naturel de *Rhynchophorus palmarum* (L.) (Coleoptera: Curculionidae). *Oléagineux*, **48**, 219–223 [12.1.6.6; 12.2.6.1]
- Moureaux J. (1952) Pathologie de *Elaeis guineensis* Jacq. In: *Notions de culture de l'Elaeis au Congo Belge* (Ed. by R. Vanderweyen), pp. 129–149, Direction de l'Agriculture, des Forêts, des Elevages et de la Colonisation, Brussels [12.1; 12.1.6.2]
- Munevar F. (1998) Problemas de los suelos cultivados con palma de aceite en Colombia. *Palmas (Bogota)*, **19**, 218–228 [3.5.3]
- Munevar F., Acosta A. & Gomez P.L. (2001) Factores edáficos asociados con la pudrición de cogollo de la palma de aceite en Colombia. *Palmas (Bogota)*, **22**, 9–19 [12.1.7.2]
- Munns R. (1993) Physiological processes limiting plant growth in saline soils: some dogmas and hypotheses. *Pl. Cell Environ.*, **16**, 15–24 [3.4.3.4]
- Murase M., Sajuga, Makagiansar I.T., Haska H.N. & Ramelan S.W. (1997) Acyl-ACP thioesterase cDNAs from oil palm. Paper presented at Plant Molecular Biology Conf., Singapore. [6.6.2.1]
- Murashige T. & Skoog F. (1962) A revised medium for rapid growth and bioassays with tobacco tissue culture. *Physiol. Pl.*, **15**, 473–497 [6.2.1]
- Mustafa M. (2000) Mechanised weeding operations – a United Plantations experience. *Planter, Kuala Lumpur*, **76**, 87–96 [10.1.3.3]
- Nadarajah P. (1980) Species of Endogonaceae and mycorrhizal association of *Elaeis guineensis* and *Theobroma cacao*. In: *Tropical mycorrhiza research* (Ed. by P. Mikola), pp. 232–237, Oxford Science Publishers, Oxford [2.2.1.5; 11.2.2]
- Naert B., Gal R., Lubis A.U., Suwandi & Olivin J. (1990) Preliminary evaluation of the possibilities of using spatial remote sensing to study developments on an oil palm plantation in North Sumatra. *Oléagineux*, **45**, 201–214 [10.7.5; 11.4.1.1]
- Nampoothiri K.U.K. (2001) Organic farming – its relevance to plantation crops. *J. Plantation Crops*, **29**, 1–9 [1.6.2]
- Nascimento J.C., Da Silva E.B., Ooi S.C., Maia A.d.S. & Muller A.A. (1982) First Brazilian national oil palm research programme. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 427–434, Incomp. Soc. Planters, Kuala Lumpur [1.4.3.8; 5.1.4.4]
- Nasir Amiruddin M. & Abdullah R. (2000) Marketing of palm oil. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 1462–1493, Malaysian Palm Oil Board, Kuala Lumpur [14.1.1; 14.1.3]
- Nasir Amiruddin M. & Basiron Y. (1993) Comparative benefit for the palm oil industry. In: *Proc. 1991 Int. Palm Oil Conf. – Promotion and marketing* (Ed. by Y. Basiron et al.), pp. 24–33, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.2.1]
- Nathan L. (2000) The right approach to effective herbicide application. *Planter, Kuala Lumpur*, **76**, 109–116 [10.1.3.3]
- Navaratnam S.J. (1961) Successful inoculation of oil palms with a pure culture of *Ganoderma lucidum*. *Malay. agric. J.*, **43**, 233–238 [12.1.6.3]
- Navaratnam S.J. & Chee K.L. (1965) Stem rot of oil palms in the Federal Experiment Station, Serdang. *Malay. agric. J.*, **45**, 175–181 [12.1.6.5]
- Nawi che Yusoff, Leong C.W. & Jamaludin Lamin (1984) *Intercropping cocoa and oil palm – eleven years of trial results*. Paper presented at Int. Conf. 'Cocoa and coconuts', 15–17 Oct., Kuala Lumpur [9.3.4]
- Nazeeb M. (1997) Agronomic practices to remain competitive in the oil palm industry. *Planter, Kuala Lumpur*, **73**, 533–553 [9.2.1]
- Nazeeb M., Loong S.G. & Wood B.J. (1988) Trials on reducing the non-productive period at oil palm replanting. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan et al.), pp. 372–390, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [7.2.3; 8.3.4.3]
- Nazeeb M., Loong S.G., Goh K.H. & Wood B.J. (1990) Trials on planting oil palms at high initial density with later thinning. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani et al.), pp. 199–214, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [9.3.6.2; 9.3.6.3]
- Nazeeb M., Loong S.G., Letchumanan A., Yoong C.P., Toh C.Y. & Goh B.P. (1993) Sime Darby's early experience with oil palm advanced planting material. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron et al.), pp. 219–225, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [7.2.3; 9.1.5; 9.2.1]
- Nazeeb M., Tang M.K., Letchumanan A. & Loong S.G. (1995) Trials on cessation of manuring before replanting. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani et al.), pp. 293–312, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.4.2; 8.3.4.3; 11.3.2.3; 11.7.1]
- Nazeeb M., Loong S.G., Letchumanan A. & Tang M.K. (1996) Alternative methods of replanting oil palms. *Planter, Kuala Lumpur*, **72**, 221–231 [9.2.1]
- Nazeeb M., Barakabah S.S. & Loong S.G. (2000) Potential of

- high density oil palm plantings in diseased environments. *Planter, Kuala Lumpur*, **76**, 699–710 [9.3.6.1; 12.1.6.3]
- Ndon B.A. (1985) Germination of oil palm seeds as affected by duration of seed storage, heat treatment, soaking and scarification. *J. Nigerian Inst. Oil Palm Res.*, **7**, 85–97 [7.1.4.4]
- Nelson S.P.C. (1993) Producción de semillas clonal y sexual en Dami – futuros desarrollos. *Palmas, (Bogota)* **14** (Special no.) [5.3.3.1]
- Nelson S.P.C. & Caligari P.D.S. (2002) *The value of cross prediction in oil palm breeding*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [6.4.1]
- Nelson S.P.C., Kohar M. & Caligari P.D.S. (2000) *A new breeding strategy for commercial and breeding oil palm populations*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [6.4.1]
- Ng B.H., Corley R.H.V. & Clegg A.J. (1976) Variation in the fatty acid composition of palm oil. *Oléagineux*, **31**, 1–8 [5.3.7.2]
- Ng K.Y. (1982) *Venturia palmaris* Wilkinson (Hymenoptera: Ichneumonidae) – a parasite of oil palm bunch moth *Tirathuba rufivena* Walker (Lepidoptera: Pyralidae). In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 519–528, Incomp. Soc. Planters, Kuala Lumpur [12.2.8.1]
- Ng P.H.C., Chew P.S., Goh K.J. & Kee K.K. (1999) Nutrient requirements and sustainability in mature oil palms – an assessment. *Planter, Kuala Lumpur*, **75**, 331–345 [11.1.4; 11.3.2.3; 11.6.1.2; 11.6.1.3; 11.6.2.2]
- Ng S.K. (1977) Review of oil palm nutrition and manuring – scope for greater economy in fertiliser usage. *Oléagineux*, **32**, 197–209 [11.1.3.1; 11.1.4; 11.6.1.1; 11.7.1; 11.9.4]
- Ng S.K. & Thamboo S. (1967) Nutrient contents of oil palms in Malaya. I. Nutrients required for reproduction: fruit bunches and male inflorescence. *Malay. agric. J.*, **46**, 3–45 [11.6.2.6; 11.7.1; 11.7.2.1]
- Ng S.K. & Thong K.C. (1985) Nutrient requirements for exploiting yield potentials of major plantation tree crops in the tropics. In: *Potassium in the agricultural systems of the humid tropics*, *Proc. 19th Colloquium Int. Potash Inst.*, pp. 55–69, Int. Potash Inst., Berne [10.7.3]
- Ng S.K., Thamboo S. & de Souza P. (1968) Nutrient contents of oil palms in Malaya. II. Nutrients in vegetative tissues. *Malay. agric. J.*, **46**, 332–391 [4.1.2.1; 11.1.2; 11.1.4; 11.6.2.6; 11.7.1]
- Ngui M. & Khoo S.N. (1982) An empirical modification to the method of germinating seeds in commercial oil palm seed production. *Dept Agric., Sabah, Malaysia, Tech. Bull.*, **6** [7.1.4.1]
- Nguyen H.V., Lukman F., Caliman J.P. & Flori A. (1995) Spot image as a visual tool to assess sanitary, nutrient and general status of estate oil palm plantation. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani et al.), pp. 548–554, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.7.5; 11.4.1.4]
- Nicol M. & Maudet M. (2000) Caroténoides et vitamine A. Actualités. *Ol Corps Gras Lipides*, **7**, 266–270 [14.4.3]
- Nicolas M.J.V. & Bowen M.R. (1999) *A field-level approach to coastal peat and coal-seam fires in South Sumatra province, Indonesia*, Forest Fire Prevention and Control Project, Palembang, Indonesia [8.3.6]
- Nielsen A. (1999) Progress and trends in field mechanisation. *Planter, Kuala Lumpur*, **75**, 305–316 [10.4.7]
- Nieto L.E. (1992) Sintomas y evolución del complejo pudrición de cogollo de la palma de aceite en los Llanos Orientales de Colombia. *Palmas (Bogota)*, **13** (2), 67–74 [12.1.7.2]
- Nieuwolt S., Zaki M.G. & Gopinathan B. (1982) *Agro-ecological regions in Peninsular Malaysia*. Malaysian Agric. Res. Dev. Inst., Kuala Lumpur [8.1.5.4; 10.7.3]
- Njoku J.E. (1983) The producer in the palm oil export of South Eastern Nigeria in the era of 'legitimate commerce'. *African Rev.*, **10**, 63–76 [1.2.3]
- Noel J.M., Rouziere A., Graille J. & Pina M. (1997a) Procédé DRUPALM: du nouveau pour les huileries de palme. *Ol Corps Gras Lipides*, **4**, 38–42 [13.4.3.5]
- Noel J.M., Ecker P., Rouziere A., Graille J. & Pina M. (1997b) Drupalm: a new asset for palm oil mills. II. Results. *Plantations, Recherche, Développement*, **4** (3), 247–251 [13.4.3.5; 13.4.5.2]
- Noiret J.M. & Ahizi Adiapa P. (1970) Anomalies de l'embryon de palmier à huile. Applications à la production des semences. *Oléagineux*, **25**, 511–517 [7.1.4.4]
- Noiret J.M., Gascon J.P. & Bénard G. (1966) Contribution à l'étude de l'hérédité des caractéristiques de la qualité du régime et du fruit d'*Elaeis guineensis* Jacq. Application à la sélection du palmier à huile. *Oléagineux*, **21**, 343–350 [5.4.2.1]
- Noiret J.M., Gascon J.P. & Pannetier C. (1985) Oil palm production through *in vitro* culture. *Oléagineux*, **40**, 365–372 [6.2.1.1]
- Nortcliff S. (1988) Soil survey, soil classification and land evaluation. In: *Soil conditions and plant growth* (Ed. by A. Wild), Longmans, Harlow and Wiley, New York [3.4.1.2]
- Nouy B., Asmady & Lubis R. (1990) Effects of interpalp competition in oil palm genetic trials in North Sumatra. Implications for the evaluation of planting material. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani et al.), pp. 467–475, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.4.4]
- Nouy B., Lubis R.A., Kusnadi T.T., Akiyat & Samaritaan G. (1991) Oil palm (*Elaeis guineensis*) production potential results for Deli × La Mé hybrids in North Sumatra. *Oléagineux*, **46**, 91–99 [5.5.1.3; 5.5.2.3]
- Nouy B., Omore A. & Potier F. (1996) Oil palm production cycles in different ecologies: consequences for breeding. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin et al.), pp. 62–75, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.5.1]
- Nouy B., Baudouin L., Djegui N. & Omore A. (1999) Oil palm under limiting water supply conditions. *Plantations, Recherche, Développement*, **6**, 31–45 [3.3.1; 3.5.2.2; 5.3.6.1; 8.1.5.2]
- Núñez Virrueta J.I. (1998) Programa nacional de palma africana de aceite en México. *Palmas (Bogota)*, **19** (Special no.), 85–89 [1.4.3.12]
- Nwankwo B.A. & Krikorian A.D. (1983) Morphogenetic potential of embryo- and seedling-derived callus of *Elaeis guineensis* Jacq. var. *pisifera* Becc. *Ann. Bot.*, **51**, 65–76 [6.2.1; 6.2.1.2]
- Nwanze S.C. (1965) The hydraulic hand press. *J. Nigerian Inst. Oil Palm Res.*, **4**, 290–316 [13.4.4]
- Nye P.H. & Greenland D.J. (1960) *The soil under shifting cultivation*, CAB International, Wallingford [1.2.2; 8.3.2]
- Nye P.H. & Tinker P.B. (1977) *Solute movement in the soil-root system*. Blackwell Scientific Publications, Oxford [11.1.1; 11.2.1.1]
- Obasola C.O. (1973a) Breeding for short-stemmed oil palm in Nigeria. I. Pollination, compatibility, varietal segregation, bunch quality and yield of F1 hybrids *Corozo oleífera* × *Elaeis guineensis*. *J. Nigerian Inst. Oil Palm Res.*, **5** (18), 43–54 [2.4]

- Obasola C.O. (1973b) Female sterility and fertility in variety *pisifera* and shell thickness in progenies of *dura* × *pisifera* crosses of the oil palm (*Elaeis guineensis* Jacq.). *J. Nigerian Inst. Oil Palm Res.*, **5** (18), 37–41 [5.4.2.3]
- Obasola C.O., Obisesan I.O. & Opute F.I. (1977) Breeding of short-stemmed oil palm in Nigeria. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 68–94, Incomp. Soc. Planters, Kuala Lumpur [5.5.1.6]
- Obisesan I.O. & Parimoo R.D. (1985) Stability and adaptation responses of Dumpy Deli palms (*Elaeis guineensis* Jacq.) to different environments. *Malay. appl. Biol.*, **14**, 84–88 [5.5.1.7]
- Oboh B.O. (1993) The development of short stemmed oil palm 1 – the *Elaeis oleifera* approach. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 492–496, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [2.3.2; 5.5.1.6]
- Ochoa G. & Bustamante E. (1974) Investigación del agente causal de la pudrición de flecha en palma africana. *Revista Inst. Colomb. Agropec.*, **9**, 425–433 [12.1.7.2]
- Ochs R. (1963) Recherches de pédologie et de physiologie pour l'étude du problème de l'eau dans la culture du palmier à huile. *Oléagineux*, **18**, 231–238 [4.4.3.1]
- Ochs R. & Daniel C. (1976) Research on techniques adapted to dry regions. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 315–330, Elsevier, Amsterdam [3.2.3; 4.3.3; 4.5.2; 4.5.3; 10.1.2.3; 10.3]
- Ochs R. & Quencez P. (1982) Method of estimating yield by counting oil palm inflorescences and bunches. *Oléagineux*, **37**, 343–347 [4.5.4]
- Ochs R., Olivin J., Quencez P. & Hornus P. (1991) Response to potassium fertiliser on acid sands of tertiary sediments. *Oléagineux*, **46**, 1–11 [11.3.3.2]
- Odetola A. (1974a) A re-examination of large-scale germination of the oil palm seed at NIFOR. *J. Nigerian Inst. Oil Palm Res.*, **5** (19), 33–40 [7.1.4.1]
- Odetola A. (1974b) Heat requirement of oil palm seeds for germination – relation of seed age to heat requirement. *J. Nigerian Inst. Oil Palm Res.*, **5** (19), 79–84 [7.1.4.1; 7.1.4.4]
- Odewale J.O. (1989) *Tissue culture research on oil palm in Nigeria*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [6.6.1.1]
- Oehlschlager A.C., Pierce H.D., Morgan B., Wimalaratne P.D.C., Slessor K.N., King G.G.S., Gries G., Gries R., Borden J.H., Jiron L.F., Chinchilla C.M. & Mexzon R.G. (1992) Chirality and field activity of rhynchophorol, the aggregation pheromone of the American palm weevil. *Naturwiss.*, **79**, 134–135 [12.2.6.1]
- Oehlschlager A.C., Chinchilla C.M., Gonzalez L.M., Jiron L.F., Mexzon R. & Morgan B. (1993) Development of a pheromone-based trapping system for *Rhynchophorus palmarum* (Coleoptera: Curculionidae). *J. Econ. Entomol.*, **86**, 1381–1392 [12.1.6.6]
- Ogunkunle A.O., Omoti U., Aghimien A.E. & Isenmila A.E. (1999) Characteristics, classification and agricultural potential of some Niger Delta soils in Nigeria. *Comm. Soil Sci. Pl. Analysis*, **30**, 663–675 [3.5.2.1; 8.1.5.2]
- Oh L.K. (1983) Depericarper design and operation. In: *Proc. Regional Workshop 'Palm oil mill technology and effluent treatment'*, pp. 36–45, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.3.7]
- Oil World (2000) *Oil world annual*. Mielke, Hamburg [1.4.1; 1.4.2.4; 1.4.3.3; 1.4.3.5]
- Ojanuga A.G., Lekwa G. & Akamigbo F.R.O. (1981) Survey genesis and classification of acid sands. In: *Acid sands of southern Nigeria, SSSN Special Publication Monograph, No. 1*, pp. 1–18, Soil Sci. Soc. Nigeria [3.5.2.1]
- Okpala-Jose A. (1995) Relating the performance of oil palm to microclimatic changes at varying distances the palms and adjacent cassava stands. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 603–613, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.4.3.1]
- Okwuagwu C.O. (1988) The genetic basis for the low correlation between *dura* and *tenera* fullsib shell to fruit ratio in the oil palm (*Elaeis guineensis* Jacq.). In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 143–154, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.3.1; 5.3.3.2]
- Okwuagwu C.O. (1989) *The developments from the comprehensive oil palm breeding programme of the Nigerian Institute for Oil Palm Research (NIFOR) and future breeding strategy*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [5.1.6.1; 5.3.2; 5.4.4]
- Okwuagwu C.O. (1993) The genetic improvement of the Deli *dura* breeding population. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), p. 491, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.1; 5.1.7.5; 5.3.2]
- Okwuagwu C.O. & Okolo E.C. (1992) Maternal inheritance of kernel size in the oil palm, *Elaeis guineensis* Jacq. *Elaeis*, **4**, 72–78 [5.3.3.1]
- Okwuagwu C.O. & Okolo E.C. (1994) Genetic control of polymorphism for kernel-to-fruit ratio in the oil palm (*Elaeis guineensis* Jacq.). *Elaeis*, **6**, 75–81 [5.3.3.1]
- Okwuagwu C.O. & Tai G.C.C. (1995) Estimation of variance components and heritability of bunch yield and yield components in the oil palm (*Elaeis guineensis* Jacq.). *Pl. Breed.*, **114**, 463–465 [5.2.3]
- Olie J.J. (1969) Some factors affecting the bleachability of palm oil. In: *The quality and marketing of palm oil products* (Ed. by P.D. Turner), pp. 32–41, Incomp. Soc. Planters, Kuala Lumpur [13.4.6.2]
- Olie J.J. & Tjeng T.D. (1974) Kernel recovery. In: *The extraction of palm oil*, pp. 63–69, Stork, Amsterdam [13.4.3.5; 13.4.3.7]
- Oliver A. & King G. (1996) *Country report – Papua New Guinea: fertiliser research for sustainable yields in Papua New Guinea*. Paper presented at Conf. 'Sustainability of oil palm plantations – agronomic and environmental perspectives', 27 Sept., Int. Soc. Oil Palm Agronomists, Kuala Lumpur [11.3.3.2]
- Olivin J. (1966) Pointe annuelle de production des palmeraies au Dahomey et cycle annuel de développement du palmier à huile. *Oléagineux*, **21**, 351–354 [4.4.6; 4.4.8]
- Olivin J. (1968) Etude pour la localisation d'un bloc industriel de palmiers à huile. II. Les critères de jugement. *Oléagineux*, **23**, 499–504 [3.2.3; 3.4.2.1; 8.1.5.2; 8.1.5.3]
- Olivin J. (1986) Study for the siting of a commercial oil palm plantation. *Oléagineux*, **41**, 113–118, 175–182 [3.2.1; 3.4.2.1; 4.2.1; 8.1.5.2]
- Ollagnier M. & Delvaux R. (1966) La plantation du Val d'Iguape. *Oléagineux*, **21**, 663–667 [9.1.4.1]
- Ollagnier M. & Ochs R. (1971a) Chlorine, a new essential element in oil palm nutrition. *Oléagineux*, **26**, 1–16 [11.4.5.1]
- Ollagnier M. & Ochs R. (1971b) The chlorine nutrition of oil palm and coconut. *Oléagineux*, **26**, 367–372 [11.4.5.1]

- Ollagnier M. & Renard J.L. (1976) Influence du potassium sur la résistance du palmier à huile à la fusariose. *Oléagineux*, **31**, 203–209 [12.1.6.2]
- Ollagnier M. & Valverde G. (1968) Contribution à l'étude de la carence en bore du palmier à huile. *Oléagineux*, **23**, 359–366 [12.1.5.3]
- Ollagnier M., Ochs R. & Martin G. (1970) The manuring of the oil palm in the world. *Fertilité*, **36**, 3–63 [8.1.2]
- Ollagnier M., Daniel C., Fallavier P. & Ochs R. (1988) The influence of climate and soil on potassium critical level. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 235–248, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.4.2.1; 11.4.3; 11.4.4.1; 11.4.4.3; 11.8.2]
- Omereji G.O. (1995) Meeting Nigeria's oil needs: smallholder or large scale plantation approach. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 584–594, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.4.3.4; 1.5.3]
- Omoti U. (2001) *Recent developments in the oil palm industry in Nigeria*. Paper presented at Conf. 'The future of the oil palm industry in Africa and strategies for development', 12 Sept., African Oil Palm Development Association/African Development Bank, Abidjan [1.4.3.4]
- Omoti U., Isenmila A.E. & Ataga D.O. (1988) Studies of the water-balance in oil palm plantations on an acid soil in Southern Nigeria. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'*, (Ed. by A. Halim Hassan *et al.*), pp. 309–320, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.2.2.1]
- Ong A.S.H., Halim Hassan A., Basiron Y., Choo Y.M. & Gapor Mohd Top A. (1990) Palm vitamin E and palm diesel pilot plants. In: *Proc. Symp. 'New developments in palm oil'* (Ed. by K.G. Berger), pp. 45–55, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.3.6.2; 14.4.3]
- Ong E.C., Lee C.H., Law I.H. & Ling A.H. (1986) Genotype–environment interaction and stability analysis for bunch yield and its components, vegetative growth and bunch characters in the oil palm (*Elaeis guineensis* Jacq.). In: *'New frontiers in breeding research', Proc. 5th Int. Congr. SABRAO* (Ed. by B. Napompeth & S. Subhadrabandhu), pp. 523–532, Soc. Breeding Res. Asia & Oceania, Bangkok [5.5.1.7]
- Ong H.T. (1982a) System approach to the climatology of oil palm. II. Identification of temperature and sunshine aspects. *Oléagineux*, **37**, 443–450 [4.4.5.1; 4.5.3]
- Ong H.T. (1982b) System approach to the climatology of oil palm. I. Identification of rainfall and dry spell aspects. *Oléagineux*, **37**, 93–101 [4.5.3]
- Ong S.H., Boey P.L. & Wong P.G. (1977) Application of the direct method of olein determination to crude palm oil and fractionation study of oils from *Melanococca* hybrid palms. *MARDI Res. Bull.*, **5**, 29–39 [5.3.7.1]
- Ong S.H., Chuah C.C. & Sow H.P. (1981) The co-dominance theory: genetic interpretations of analyses of mesocarp oils from *Elaeis guineensis*, *Elaeis oleifera* and their hybrids. *J. Amer. Oil Chem. Soc.*, **58**, 1032–1038 [5.3.7.1]
- Oo K.C. (1986) Biochemistry of the germinated oil palm seedling. *Palm Oil Res. Inst. Malaysia, Bull.*, **12**, 36–41 [2.2.1.2]
- Oo K.C., Lee K.B. & Ong A.S.H. (1986) Changes in fatty-acid composition of the lipid classes in developing oil palm mesocarp. *Phytochemistry*, **25**, 405–407 [13.3]
- Ooi C.K., Choo Y.M., Yap S.C., Basiron Y. & Ong A.S.H. (1994) Recovery of carotenoids from palm oil. *J. Amer. Oil Chem. Soc.*, **71**, 423 [14.4.3]
- Ooi L.H. & Sim B.S. (1997) Impact of two improved practices on labour requirements and production costs in oil palm estates. In: *Plantation management for the 21st century* (Ed. by E. Pushparajah), pp. 371–383, Incomp. Soc. Planters, Kuala Lumpur [10.2.1; 10.4.6]
- Ooi L.H. & Tey S.H. (1998) *Application of global positioning system and geographical information system in oil palm estates*. Paper presented at Natn. Seminar 'Mechanisation in oil palm plantations', Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.2.1]
- Ooi L.H., Goh T.M., Ang B.N. & Tan K.S. (2001) A new method of clearing oil palms for replanting. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 151–158, Malaysian Palm Oil Board, Kuala Lumpur [8.3.4.2; 12.2.4.1]
- Ooi S.C. (1975a) Variability in the Deli *dura* breeding population of the oil palm (*Elaeis guineensis* Jacq.). II. Within bunch components of yield. *Malay. agric. J.*, **50**, 20–30 [5.3.3.2]
- Ooi S.C. (1975b) Variability in the Deli *dura* breeding population of the oil palm (*Elaeis guineensis* Jacq.). III. An outcrossed population. *Malay. agric. J.*, **50**, 147–153 [5.1.6; 5.3.2; 5.3.3.2]
- Ooi S.C. (1978) Variability in the Deli *dura* breeding population of the oil palm (*Elaeis guineensis* Jacq.). IV. Growth and physiological parameters. *Malay. agric. J.*, **51**, 359–365 [5.3.4.1]
- Ooi S.C. & Tam T.K. (1976) The determination of the within bunch components of oil yield in the oil palm (*Elaeis guineensis* Jacq.). I. Pattern of variation. *Planter, Kuala Lumpur*, **52**, 467–475 [5.2.4.2]
- Ooi S.C., Hardon J.J. & Phang S. (1973) Variability in the Deli *dura* breeding population of the oil palm (*Elaeis guineensis* Jacq.). I. Components of bunch yield. *Malay. agric. J.*, **49**, 112–121 [5.3.2; 5.5.2.2]
- Ooi S.C., Da Silva E.B., Muller A.A. & Nascimento J.C. (1981) Oil palm genetic resources – native *E. oleifera* populations in Brazil offer promising sources. *Pesq. Agropec. Brasil.*, **16**, 385–395 [2.3.2; 5.1.7.3]
- Ooi S.C., Nascimento J.C. & Da Silva E.B. (1982) The oil palm industry in Brazil – current status and future potential. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 369–392, Incomp. Soc. Planters, Kuala Lumpur [1.4.3.8]
- Ooi S.H., Woo Y.C. & Leng K.Y. (1990) Yield maximisation and conservation in tree crop agriculture with special reference to oil palms and cocoa. In: *Proc. Int. Conf. 'Tropical biodiversity: in harmony with nature'*, pp. 501–519, Malaysian Nature Soc., Kuala Lumpur [10.7.1]
- Opsomer J.K. (1956) Les premières descriptions de palmier à huile (*Elaeis guineensis* Jacq.). *Bull. Séances Acad. R. Soc. Colon. (Oltre Mer)*, **2**, 253–272 [1.1.2]
- Oritsejafor J.J. (1989) *Status of the oil palm vascular wilt disease in Nigeria*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [12.1.6.2]
- Osborne D.J., Henderson J. & Corley R.H.V. (1992) Controlling fruit-shedding in the oil palm. *Endeavour*, **16**, 173–177 [2.2.2.7]
- Owolarafe O.K., Faborode M.O. & Ajibola O.O. (2002) Comparative evaluation of the digester-screw press and a hand-operated hydraulic press for palm fruit processing. *J. Food Engineering*, **52**, 249–255 [13.4.4]

- Pabon Silva H. (1985) Sistemas de riego en palma africana: eficiencia y costos. *Palmas (Bogota)*, 6 (1), 38–40 [10.3.1.1]
- Pacheco A.R., Tailliez B.J., de Souza R.L.R. & de Lima E.J. (1985) Mineral deficiencies of oil palm (*Elaeis guineensis* Jacq.) in the Belem (Para) region, Brazil. *Oléagineux*, 40, 295–309 [11.3.3.1]
- Pacheco A.R., Barnwell I.M. & Tailliez B.J. (1986) Des cas de déficience en cuivre en pépinière de palmiers à huile en Amazonie brésilienne. *Oléagineux*, 41, 483–489 [11.8.5]
- Palat T. & Corley R.H.V. (2002) *Replanting oil palms by underplanting with various thinning and pruning techniques: an experiment and practical experience in Southern Thailand*. Paper presented at Int. Palm Oil Conf., 8–12 July, Indonesian Oil Palm Res. Inst., Bali [8.3.4.3; 9.2.1]
- Palat T., Chayawat N., Rao V. & Corley R.H.V. (1999) *The oil palm breeding programme of Unicanich of Thailand*. Paper presented at 1999 PORIM Int. Palm Oil Congr., 1–6 Feb., Kuala Lumpur [5.1.6.2]
- Palat T., Smith B.G. & Corley R.H.V. (2000) Irrigation of oil palm in Southern Thailand. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 303–315, Incomp. Soc. Planters, Kuala Lumpur [1.4.3.3; 3.3.3; 4.3.3.2; 10.3]
- Pamin K. (1995) Obituary – SP540. *Int. Soc. Oil Palm Breeders Newslett.*, 11, 1–2 [5.1.1.3]
- Pamin K. (1998) A hundred and fifty years of oil palm development in Indonesia: from the Bogor Botanical Garden to the industry. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 3–23, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.3.2; 1.4.3.1; 1.5.4; 1.6.3.1; 2.2.1.3; 5.1.1.1; 5.1.1.2]
- Pandya-Lorch R., Pinstrip-Andersen P. & Rosegrant M.W. (2001) Prospects for food demand and supply towards 2020. *Proc. Fertiliser Soc.* [1.4.2.1]
- Parakh R.L. & Pathak M.P. (2000) The palm oil refining and palm products manufacturing – an experience. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 835–842, Incomp. Soc. Planters, Kuala Lumpur [13.4.6.2; 13.4.7; 13.5.1]
- Paramanathan S. (1987a) Field legend for a soil survey in Malaysia. In: *Penerbit, Universiti Pertanian Malaysia, Serdang, Malaysia* [3.4.1.3]
- Paramanathan S. (1987b) Soil suitability and management implications of soil taxonomy with special reference to tree crop cultivation. *Pertanika J. Trop. Agric. Sci.*, 10, 125–134 [3.4.2.2]
- Paramanathan S. (1995) *Soil survey and management on tropical soils*. Training course note, Param Agric. Surv., Kuala Lumpur [3.4.1; 3.5.1.2]
- Paramanathan S. (1998) *Malaysian soil taxonomy (second approximation)*. Malaysian Soc. Soil Sci./Param Agric. Surveys [3.4.1.2; 3.4.1.3; 3.4.3.7]
- Paramanathan S. (2000a) Soil requirements of oil palm for high yields. In: *Managing oil palm for high yields: agronomic principles* (Ed. by Goh K.J.), pp. 18–38, Malaysian Soc. Soil Sci./Param Agric. Surveys, Kuala Lumpur [3.4.2.2; 3.4.3.6; 3.4.3.7; 3.4.3.8; 8.1.3.4]
- Paramanathan S. (2000b) *Soils of Malaysia – their characteristics and identification*, Vol. I, Acad. Sci. Malaysia [3.4.1.3; 3.5.1.1]
- Paramanathan S., Chew P.S. & Goh K.J. (2000) Towards a practical framework for land evaluation for oil palm in the 21st century. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 869–885, Incomp. Soc. Planters, Kuala Lumpur [3.3.1; 3.4.2.2; 8.1.2; 8.1.3; 8.1.5.1; 8.1.5.4; 8.2.3]
- Paranjothy K. (1986) Recent developments in cell and tissue culture of oil bearing palms. *Palm Oil Res. Inst. Malaysia, Occ. Paper*, 19, 1–12 [6.2.1]
- Paranjothy K. & Rohani O. (1982) *In vitro* propagation of oil palm. In: *Proc. 5th Int. Congr. 'Plant tissue and cell culture'* (Ed. by F. Fujiwara), pp. 747–748, Jpn. Assoc. Plant Tissue Culture, Tokyo [6.2.1; 6.2.1.2; 6.2.1.3]
- Paranjothy K., Rohani O., Tarmizi A.H., Tan C.S. & Tan C.C. (1990) Current status and strategies of oil palm tissue culture research. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 109–121, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.2.1.1; 6.2.2.2; 6.3.1.2; 6.3.2; 6.5.2]
- Paranjothy K., Rohani O., Tan C.C., Wong G. & Soh A.C. (1995a) Incidence of abnormalities in relation to *in vitro* protocols. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 77–85, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.2.1.2; 6.3.1.1; 6.3.1.2]
- Paranjothy K., Ong L.M. & Sharifah S. (1995b) DNA and protein changes in relation to clonal abnormalities. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 86–97, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.3]
- Parveez G.K.A. (2000) Production of transgenic oil palm (*Elaeis guineensis* Jacq.) using biolistic techniques. In: *Molecular biology of woody plants*, Vol. 2 (Ed. by S.M. Jain & S.C. Minocha), pp. 327–350, Kluwer Academic, Dordrecht [6.6.2.3]
- Parveez G.K.A., Chowdhury M.K.U. & Saleh N.M. (1994) Current status of genetic engineering in oil bearing crops. *Asia Pacific J. Molec. Biol. Biotechnol.*, 2, 174–192 [6.6.2.1]
- Parveez G.K.A., Chowdhury M.K.U. & Saleh N.M. (1996) Determination of minimal inhibitory concentration of selection agents for oil palm (*Elaeis guineensis* Jacq.) transformation. *Asia Pacific J. Molec. Biol. Biotechnol.*, 4, 219–228 [6.6.2.3]
- Parveez G.K.A., Chowdhury M.K.U. & Saleh N.M. (1997) Physical parameters affecting transient GUS gene expression in oil palm (*Elaeis guineensis* Jacq.) using the biolistic device. *Ind. Crops Products*, 6, 41–50 [6.6.2.3]
- Parveez G.K.A., Chowdhury M.K.U. & Saleh N.M. (1998a) Biological parameters affecting transient GUS gene expression in oil palm (*Elaeis guineensis* Jacq.) embryogenic calli via microprojectile bombardment. *Ind. Crops Products*, 8, 17–27 [6.6.2.3]
- Parveez G.K.A., Tahir F., Harikrishna K., Napis S., Cheah S.C. & Christou P. (1998b) *Production of transgenic oil palm (Elaeis guineensis Jacq.) via microprojectile bombardment*. Paper presented at Congress on *In Vitro* Biology, June, Las Vegas [6.6.2.3]
- Parveez G.K.A., Sambanthamurthi R., Siti Nor Akmar A., Othman A., Ramli U.S., Rasid O., Masri M.M. & Cheah S.C. (1999) Production of transgenic oil palm – current success and future considerations. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 283–296, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.6.2; 6.6.2.3]
- Patino V.M. (1948) Información preliminar sobre la palma de aceite africana (*Elaeis guineensis*) en Colombia. *Estacion Agro*

- forestal del Pacifico de Calima Buenaventura, Serie Bot. Apl., 1 (2) [5.1.4.2]
- Patiño V.M. (1958) La palma de aceite africana (the African oil palm). *Economica Colombiana*, 19, 93–97 [5.1.4.2]
- Paul T.C. (1995) *Fusarium wilt of oil palm: studies on resistance and pathogenicity*. Thesis, University of Bath [12.1.6.2]
- Penning de Vries F.W.T. (1972) Respiration and growth. In: *Crop processes in controlled environments* (Ed. by A.R. Rees et al.), pp. 327–346, Academic Press, London [4.1.4.3; 4.3.5.2]
- Penning de Vries F.W.T. (1975) The cost of maintenance processes in plant cells. *Ann. Bot.*, 39, 77–92 [4.1.4.3]
- Peralta F., Vasquez O., Richardson D.L., Alvarado A. & Bornemisza E. (1985) Effect of some soil physical characteristics on yield, growth and nutrition of the oil palm in Costa Rica. *Oléagineux*, 40, 423–430 [11.2.1.3]
- Peralta F., Montoya C. & Escobar R. (1998) Oil and kernel extraction rates in the oil palm industry in Costa Rica, Central America – country report. In: *Proc. 1996 Int. Conf. 'Oil and kernel production in oil palm – a global perspective'* (Ed. by N. Rajanaidu, I.E. Henson & B.S. Jalani), pp. 306–316, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.5.2]
- Periasamy A., Gopal K. & Soh A.C. (2002) Productivity improvements in seed processing techniques for commercial oil palm seed production. *Planter, Kuala Lumpur*, 78, 429–442 [7.1.3]
- Perthuis B., Desmier de Chenon R. & Merland E. (1985) Revelation of the Marchitez sorpresiva vector of the oil palm, the bug *Lincus lethifer* Dolling (Hemiptera Pentatomidae Discocephalinae). *Oléagineux*, 40, 473–476 [12.1.6.4]
- Philippe R. (1990a) Practical chemical control methods against *Coelaenomenodera minuta* Uhmann (Coleoptera–Chrysomelidae–Hispiinae). *Oléagineux*, 45, 165–173 [12.2.5.5]
- Philippe R. (1990b) Study of Evisect S action on *Coelaenomenodera minuta* (Coleoptera–Chrysomelidae–Hispiinae). *Oléagineux*, 45, 143–163 [12.2.5.5]
- Philippe R. (1993) Study of pest incidence on female oil palm inflorescences in West Africa. *Oléagineux*, 48, 389–405 [12.2]
- Philippe R. & Diarrassouba S. (1979) Method of control of *Coelaenomenodera* by introduction of systemic insecticide into the oil palm trunk. *Oléagineux*, 34, 229–233 [12.2.5.5]
- Philippe R., Desmier de Chenon R., Lecoustre R. & Mariau D. (1979) Contribution to the biological control of *Coelaenomenodera*: introduction to the Ivory Coast of parasites of Hispiinae larvae. *Oléagineux*, 35, 277–279 [12.2.5.5]
- Pichel R. (1956) L'amélioration du palmier à huile au Congo Belge. *Bull. Agron.*, 14, 59–66 [5.1.5; 5.1.6.1; 5.1.7.1; 5.4.2.1]
- Pieri C., Dumanski J., Hamblin A. & Young A. (1995) *Land quality indicators*. World Bank Discussion Paper No. 315, World Bank, Washington, DC [8.2.1]
- Pilotti C.A. & Sanderson F.R. (2001) BSR – unravelling the mystery: the Milne Bay situation. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 641–645, Malaysian Palm Oil Board, Kuala Lumpur [12.1.6.3]
- Poeloengan Z. (1990) Physical land evaluation using a parametric method, application to oil palm plantations in North Sumatra, Indonesia. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani et al.), pp. 153–158, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.1.5.3]
- Poeloengan Z. (1995) Oil palm growth on high Ni soils. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani et al.), pp. 640–644, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.8.5]
- Poeloengan Z. (2002) *Natural and human resource capacity for sustainable development of oil palm industry in Indonesia*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [1.4.3.1]
- Poinar G.O., Jackson T.A., Bell N.L. & Basri Wahid M. (2002) *Elaeolenchus parthenonema* n.g., n.sp. (Nematoda: Sphaerularioidae: Anandranematidae n.fam.) parasitic in the palm-pollinating weevil *Elaeidobius kamerunicus* Faust, with a phylogenetic synopsis of the Sphaerularioidae Lubbock, 1861. *Syst. Parasitol.*, 52, 219–225 [12.5.1]
- Poncelet M. (1965) Plantations de palmiers à huile en terrasses sur terrains humides. *Oléagineux*, 20, 431–432 [9.1.4.1]
- Ponnamma K.N. (1999) Coccids associated with oil palm in India – a review. *Planter, Kuala Lumpur*, 75, 445–451 [12.2]
- Ponnamperuma F.N. (1984) The effect of flooding on soils. In: *Flooding and plant growth* (Ed. by T.T. Kozlowski), pp. 10–46, Academic Press, New York [3.4.3.2]
- PORIM (1985) *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*. Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.5.2]
- Porter R. (1989) *Development of high yielding oil palm planting material resistant to vascular wilt caused by Fusarium oxysporum f.sp. elaeidis*. Paper presented at Int. Conf. 'Palms and palm products', 21–25 Nov., Nigerian Inst. Oil Palm Res., Benin City [5.4.2.2; 12.1.6.2]
- Portillo Z. (1994) Sustainable farming in the Peruvian Amazon. *IDRC Rep.*, 22, 21–23 [8.4.3.4]
- Potier F., Gogor S., Asmady & Zaelani H. (2000) Planting material improvement at Socfindo oil palm estates in North Sumatra. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 87–102, Incomp. Soc. Planters, Kuala Lumpur [5.1.1.1]
- Prabowo N.E. & Foster H.L. (1998) Variation in oil and kernel extraction rates of palms in North Sumatra due to nutritional and climatic factors. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika et al.), pp. 275–286, Indonesian Oil Palm Res. Inst., Medan, Indonesia [10.5.2; 11.3.2.4]
- Prabowo N.E., Foster H.L. & Subagio A. (2002a) *Variation in oil and kernel extraction rates of oil palm with environment in North Sumatra*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [4.5.2]
- Prabowo N.E., Tohiruddin L., Fairhurst T.H., Foster H.L. & Nafisah E. (2002b) *Efficiency of fertiliser recovery by oil palm in Sumatra*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [11.6.1.4]
- Prendergast A.G. (1957) Observations on the epidemiology of vascular wilt disease of the oil palm. *J. W. Afr. Inst. Oil Palm Res.*, 2, 146–175 [9.3.6.1; 12.1.6.2; 12.1.6.3]
- Prendergast A.G. (1963) A method of testing oil palm progenies at the nursery stage for resistance to vascular wilt disease caused by *Fusarium oxysporum*. *J. W. Afr. Inst. Oil Palm Res.*, 4, 156–175 [12.1.5.5; 12.1.6.2]
- Preuss L. (1902) Die wirtschaftliche Bedeutung der Olpalme. *Tropenpflanzer*, 6, 450–476 [2.2]
- Prevot P. & Duchesne J. (1955) Densités de plantation pour le palmier à huile. *Oléagineux*, 10, 117–122 [9.3.3.1; 9.3.3.3; 9.3.4]
- Prevot P. & Ollagnier M. (1954) Peanut and oil palm foliar diag-

- nosis: interrelations of N, P, K, Ca and Mg. *Pl. Physiol.*, **29**, 26–34 [11.6.3]
- Prevot P. & Ollagnier M. (1957) Méthode d'utilisation du diagnostic foliaire. *Pl. Anal. Fert. Problems* [11.6.3]
- Prior R.N.B. (1988) Insect pests of oil palm in Papua New Guinea and their control. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 485–492, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.1.1; 12.2.1.4; 12.2.5.4]
- Prioux G., Jacquemard J.C., de Franqueville H. & Caliman J.P. (1992) Oil palm irrigation. Initial results obtained by PHCI (Ivory Coast). *Oléagineux*, **47**, 497–509 [8.1.5.2; 10.3]
- Pronk F. (1953) Vergelijkend tros-analytisch onderzoek van enkele typen van de oliepalm (*Elaeis guineensis* Jacq.). *Bergcultures*, **22**, 527–533, 573–581 [5.1.1.1]
- Pronk F. (1955) *De veredeling van de oliepalm door het Algemeen Proefstation der AVROS*. Internal report, AVROS, Medan, Indonesia [5.1.1.3; 5.3.3.3]
- Purba A.R., Lubis R.A. & Lubis A.U. (1995) Estimation of the combining abilities of the different *dura* and *tenera* origins studied in the first oil palm *Elaeis guineensis* breeding cycle at Marihat. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 36–54, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.2; 5.5.1.4]
- Purba P. & Lubis A.U. (1990) Land survey for oil palm plantation development in Indonesia. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 507–513, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.1.5.3]
- Purba P. & Lubis A.U. (1993) Limiting factors of oil palm yield in west part of Indonesia. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 293–301, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.5.1.2]
- Purvis C. (1956) The root system of the oil palm: its distribution, morphology and anatomy. *J. W. Afr. Inst. Oil Palm Res.*, **1** (4), 61–82 [2.2.1.5; 11.2.1.1; 11.2.1.3]
- Purvis C. (1957) The colour of oil palm fruits. *J. W. Afr. Inst. Oil Palm Res.*, **2**, 142–147 [2.2.2.6]
- Purvis M.J. (1973) Annual yield variation in oil palm: marketing board purchases in Eastern Nigeria, 1955–66. *J. Nigerian Inst. Oil Palm Res.*, **5** (18), 59–67 [4.5.4]
- Pushparajah E. (1983) The need for soil conservation in Malaysia. *Planter, Kuala Lumpur*, **59**, 513–517 [8.4.2]
- Pushparajah E. & Chew P.S. (1998) Integrated nutrient management for sustaining high yields of plantations treecrops in tropical Asia. In: *Proc. Soil Sci. Congr.*, Montpellier [11.1.4]
- Pushparajah E., Ng S.K. & Ramasingam K. (1977) Leaching losses of nitrogen, potassium and magnesium in Peninsular Malaysian soils. In: *Proc. Conf. 'Fertility and chemistry of tropical soils'*, pp. 93–105, Malaysian Soc. Soil Sci., Kuala Lumpur [11.9.2.2]
- Quah S.K. & Gillies D. (1981) Practical experience in production and use of biogas. In: *Proc. Natn. Workshop 'Oil palm by-product utilisation'*, pp. 119–126, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.8.1]
- Quah Y.T., Chew P.S. & Kiew R. (1999) An integrated weed management system for *Asystasia gangetica* subsp. *micrantha* in oil palm estates. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 497–509, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.1.2.2]
- Quencez P. (1982) Oil palm nurseries in plastic bags without shading. *Oléagineux*, **37**, 397–407 [7.2; 12.1.4]
- Quencez P. (1996) La culture du palmier à huile en Afrique intertropicale: les conditions du milieu physique. *Ol Corps Gras Lipides*, **3**, 116–118 [3.2.3; 3.3.1]
- Rabechault H. (1962) Recherches sur la culture 'in vitro' des embryons de palmier à huile (*Elaeis guineensis* Jacq.) I. Effets de l'acide β -indolylacétique. *Oléagineux*, **17**, 757–764 [7.1.1.1]
- Rabechault H. & Martin J.-P. (1976) Multiplication végétative du palmier à huile (*Elaeis guineensis* Jacq.) à l'aide de cultures de tissus foliaires. *C. R. Acad. Sci. Paris, Ser. D*, **283**, 1735–1737 [6.1]
- Radersma S. & De Ridder N. (1996) Computed evapotranspiration of annual and perennial crops at different temporal and spatial scales using published parameter values. *Agric. Water Manage.*, **31**, 17–34 [3.2.2.1]
- Rafii M.Y., Rajanaidu N., Kushairi A., Jalani B.S. & Din M.A. (2000) *Evaluation of Cameroon and Zaire genetic materials*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.1.7.2]
- Rahim Shuib A., Yaakob Hitam & Malek Mansoor (1990) Possible cost reduction and labour saving through mechanisation in Malaysian oil palm industry. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 169–174, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.2]
- Raja P., Faridah B. & Kamal M. (1999) Arbuscular mycorrhizal fungi as a possible biocontrol agent for Malaysian oil palm industry. In: *Biological control in the tropics: towards efficient biodiversity and bioresource management for effective biological control*, pp. 74–76, CABI Publishing, Wallingford, U.K. [11.2.2]
- Rajagopalan K. (1965) Plant pathology division. In: *1st Annu. Rep. Nigerian Inst. Oil Palm Res.*, pp. 86–91, Benin City [12.1.6.1]
- Rajagopalan K., Aderungboye F.O. & Obasola C.O. (1978) Evaluation of oil palm progenies for reaction to the vascular wilt disease. *J. Nigerian Inst. Oil Palm Res.*, **5** (20), 87–95 [12.1.6.2]
- Rajanaidu N. (1986a) The oil palm (*Elaeis guineensis*) collections in Africa. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 59–83, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [2.2.2.6; 5.1.7.2]
- Rajanaidu N. (1986b) *Elaeis oleifera* collection in Central and South America. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 84–94, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [2.3.1; 5.1.7.3]
- Rajanaidu N. (1987) Collection of oil palm (*Elaeis guineensis*) genetic material in Tanzania and Madagascar. *Palm Oil Res. Inst. Malaysia, Bull.*, **15**, 1–6 [2.1; 5.1.7.2]
- Rajanaidu N. & Jalani B.S. (1994a) *Oil palm genetic resources – collection, evaluation, utilisation and conservation*. Paper presented at Colloquium 'Oil palm genetic resources', 13 Sept., Palm Oil Res. Inst. Malaysia, Bangi, Malaysia [5.1.7.2; 5.1.7.3; 5.3.4.2; 5.3.7.2]
- Rajanaidu N. & Jalani B.S. (1994b) Prospects for breeding for kernels in oil palm (*Elaeis guineensis*). *Planter, Kuala Lumpur*, **70**, 307–318 [5.4.1.2]
- Rajanaidu N. & Jalani B.S. (1994c) Influence of planting material on oil extraction rate (OER). In: *Proc. Natn. Symp. 'Palm oil extraction rate: problems and issues'* (Ed. by D. Ariffin & B.S. Jalani), pp. 53–57, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.3.2]
- Rajanaidu N. & Jalani B.S. (1999a) *Proc. Seminar 'Sourcing of oil*

- palm planting materials for local and overseas joint ventures*, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.2]
- Rajanaidu N. & Jalani B.S. (1999b) World-wide production, performance and issues related to oil palm planting materials. In: *Proc. 1996 Seminar 'Sourcing of oil palm planting materials for local and overseas joint ventures'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 28–70, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1; 5.1.6; 5.4.2.2]
- Rajanaidu N. & Rao V. (1986) Performance of Nigerian oil palm genetic material. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 117–143, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.7.2]
- Rajanaidu N. & Rao V. (1987) Effective use of oil palm germplasm. *Malay. appl. Biol.*, **16**, 281–288 [5.1.7.2]
- Rajanaidu N. & Rao V. (1988) Oil palm genetic collections: their performance and use to the industry. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 59–85, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.7.2]
- Rajanaidu N., Rao V. & Tan B.K. (1983) Analysis of fatty acid composition (FAC) in *Elaeis guineensis*, *Elaeis oleifera*, their hybrids and its implications in breeding. *Palm Oil Res. Inst. Malaysia, Bull.*, **7**, 9–20 [5.1.7.2]
- Rajanaidu N., Tan Y.P. & Rao V. (1985) Harvesting and estimation of oil in a bunch. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 177–186, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.5.1]
- Rajanaidu N., Ngui M.L., Ong E.C. & Lee C.H. (1986a) Sabah breeding programme. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 175–188, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.2; 5.5.1.7]
- Rajanaidu N., Tan Y.P., Ong E.C. & Lee C.H. (1986b) The performance of inter-origin commercial D × P planting material. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 155–161, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.3; 5.5.1.7; 6.4.2]
- Rajanaidu N., Azis Ariffin A., Wood B.J. & Sarjit S. (1988) Ripeness standards and harvesting criteria for oil palm bunches. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 224–230, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.4.4]
- Rajanaidu N., Rao V., Halim H.J. Hassan A. & Ong A.S.H. (1989) Genetic resources – new developments in oil palm breeding. *Elaeis*, **1**, 1–10 [5.1.7.2; 5.1.7.4; 5.3.7.1; 5.3.7.2]
- Rajanaidu N., Jalani B.S. & Domingos M. (1991) Collection of oil palm (*Elaeis guineensis*) germplasm in Angola. *Int. Soc. Oil Palm Breeders Newsletter*, **8** (2), 2–3 [5.1.7.2]
- Rajanaidu N., Rao V., Hoong H.W., Lee C.H., Tan Y.P., Tan S.T. & Jalani B.S. (1992) Yield potential and genotype × environment (GE) studies in oil palm (*Elaeis guineensis*). In: *Proc. Workshop 'Yield potential in the oil palm'* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 44–57, Int. Soc. Oil Palm Breeders, Kuala Lumpur [5.5.1.7]
- Rajanaidu N., Jalani B.S., Rao V. & Kushairi A. (1993) Genotype–environment interaction (GE) studies in oil palm (*Elaeis guineensis*) progenies. In: *Proc. 1991 Int. Soc. Oil Palm Breeders Workshop 'Genotype–environment interaction studies in perennial tree crops'*, pp. 12–32, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.7]
- Rajanaidu N., Jalani B.S. & Kushairi A. (1998a) Oil palm genetic resources – the development of novel planting materials. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 208–220, Indonesian Oil Palm Res. Inst., Medan, Indonesia [5.1.7.4]
- Rajanaidu N., Kushairi A. & Jalani B.S. (1998b) Variation for oil and kernel to bunch, and total economic product in oil palm germplasm and breeding materials. In: *Proc. 1996 Int. Conf. 'Oil and kernel production in oil palm – a global perspective'* (Ed. by N. Rajanaidu, I.E. Henson & B.S. Jalani), pp. 19–35, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.3.2; 5.4.1.2]
- Rajanaidu N., Kushairi A., Rafii M., Mohd Din A., Maizura I. & Jalani B.S. (2000a) Oil palm breeding and genetic resources. In: *Advances in oil palm research*, Vol. I (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 171–237, Malaysian Palm Oil Board, Kuala Lumpur [5.1.7.2; 5.4.2.2]
- Rajanaidu N., Kushairi A., Rafii M.Y., Din M.A., Maizura I., Isa Z.A. & Jalani B.S. (2000b) *Oil palm genetic resources and their utilisation – a review*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.1.7.2; 5.1.7.5; 5.3.3.2; 5.3.7.4]
- Rajanaidu N., Maizura I. & Cheah S.C. (2000c) *Screening of oil palm natural populations using RAPD and RFLP molecular markers*. Paper presented at Int. Symp. 'Oil palm genetic resources and utilization', 8–10 June, Malaysian Palm Oil Board, Kuala Lumpur [5.2.8.2]
- Rajaratnam J.A. (1972a) Observations on boron-deficient oil palms (*Elaeis guineensis*). *Expl Agric.*, **8**, 339–346 [11.4.1.3; 12.1.5.3]
- Rajaratnam J.A. (1972b) White stripe disorder of oil palm (*Elaeis guineensis*) in Malaysia. *Expl Agric.*, **8**, 161–169 [12.1.5.3]
- Rajaratnam J.A. & Law I.H. (1975) Effect of boron nutrition on intensity of spider mite attack on oil palm seedlings. *Expl Agric.*, **11**, 59–63 [12.2.2]
- Rajinder S. & Cheah S.C. (1996) Flower-specific gene expression in oil palm revealed by differential display. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 583–587, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.3]
- Rajinder S., Cheah S.C., Madon M., Ooi L.C.L. & Rahman Othman A. (2001) Genomic strategies for enhancing the value of the oil palm. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 3–17, Malaysian Palm Oil Board, Kuala Lumpur [5.2.8.3; 6.3.3]
- Ramachandran P., Narayanan R. & Knecht J.C.X. (1973) A planting distance experiment on dura palms. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 72–87, Incorp. Soc. Planters, Kuala Lumpur [9.3.3.1; 9.3.3.3]
- Ramle M., Siti Ramlah A.A., Basri Wahid M. & Sharifah Azura S.I. (1995) *In vitro* studies of *Beauveria bassiana* (Bals.) Vuill. and its infection on bagworm, *Metisa plana* Wlk. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 669–683, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.1.4]
- Ramli A.M. & Duckett J.E. (1988) New techniques in irrigation and management of large oil palm nurseries. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 357–368, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [7.2.2.3]
- Rance K.A., Mayes S., Price Z., Jack P.L. & Corley R.H.V. (2001) Quantitative trait loci for yield components in oil palm (*Elaeis guineensis* Jacq.). *Theor. appl. Genet.*, **103**, 1302–1310 [5.2.8.3]
- Rankine I.R. & Fairhurst T.H. (1998a) *Field handbook – Oil palm*

- series, Vol. 1, Nursery. Potash and Phosphate Inst., Singapore [5.3.3.1; 7]
- Rankine I.R. & Fairhurst T.H. (1998b) *Field handbook – Oil palm series, Vol. 2, Immature*. Potash and Phosphate Inst., Singapore [8; 10]
- Rankine I.R. & Fairhurst T.H. (1998c) *Field handbook – Oil palm series, Vol. 3, Mature*. Potash and Phosphate Inst., Singapore [8; 10; 11]
- Rao V. & Chang K.C. (1982) Anthesis and fruit set in *Elaeis oleifera* (HBK) Cortes. *Palm Oil Res. Inst. Malaysia, Bull.*, **4**, 27–34 [2.3.2]
- Rao V. & Donough C.R. (1990) Preliminary evidence of a genetic cause for the floral abnormalities in some oil palm ramets. *Elaeis*, **2**, 199–207 [5.4.5.2; 6.3.1.2]
- Rao V. & Kushairi A. (1999) Quality of oil palm planting material. In: *Proc. 1996 Seminar 'Sourcing of oil palm planting materials for local and overseas joint ventures'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 188–197, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2.1.2]
- Rao V. & Law I.H. (1998) The problem of poor fruit set in parts of East Malaysia. *Planter, Kuala Lumpur*, **74**, 463–483 [4.4.7.1; 12.5.1]
- Rao V., Soh A.C., Corley R.H.V., Lee C.H., Rajanaidu N., Tan Y.P., Chin C.W., Lim K.C., Tan S.T., Lee T.P. & Ngui M. (1983) A critical reexamination of the method of bunch quality analysis in oil palm breeding. *Palm Oil Res. Inst. Malaysia, Occ. Paper*, **9**, 1–28 [5.2.4]
- Rao V., Rajanaidu N., Kushairi A. & Jalani B.S. (1992) Density effects in the oil palm. In: *Proc. Workshop 'Yield potential in the oil palm'* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 71–79, Int. Soc. Oil Palm Breeders, Kuala Lumpur [4.3.1.1; 9.3.3.2]
- Rao V., Jalani B.S. & Rajanaidu N. (1994) Effect of *dura* contamination on oil extraction rate (OER). In: *Proc. Natn. Seminar 'Palm oil extraction rate: problems and issues'* (Ed. by D. Ariffin & B.S. Jalani), pp. 58–60, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2.1.1; 10.5.2; 10.5.3]
- Rao V., Chia C.C. & Law I.H. (1998) *Progeny response to under-planting*. Paper presented at Int. Conf. 'Developments in oil palm industry for the 21st century', 21 Sept., Bali [8.3.4.3]
- Rao V., Law I.H., Zuraini Shaharudin & Chia C.C. (1999) *Ekona and AVROS – a tale of two pisiferas*. Paper presented at 1999 PORIM Int. Palm Oil Congr., Kuala Lumpur [5.1.1.4; 5.1.3.3; 5.5.1.2]
- Rao V., Gomez M., Chayawat N., Chia C.C. & Lim C.C. (2001) Some factors influencing oil/bunch, OER and KER. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 167–191, Malaysian Palm Oil Board, Kuala Lumpur [10.4.4; 10.5.2; 10.5.3; 13.4.5.2]
- Rashid O. & Shah F.H. (1996) The isolation, characterisation and sequencing of cDNA clones coding for stearyl-ACP desaturase gene from oil palm (*Elaeis guineensis*). In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 575–282, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.6.2.1]
- Raymond W.D. (1961) The oil palm industry. *Trop. Sci.*, **3**, 69–89 [1.1.1]
- Raynaud F.L., Maley J. & Wirmann D. (1996) Vegetation and climate in the forest of S-W Cameroun since 4770 years BP. Pollen analyses of sediments from Lake Ossa. *C. R. Acad. Sci. Ser. IIA. Sciences de la terre et des plantes*, **322**, 749 [1.1.1]
- Redshaw M.J. & Siggs A.J. (1995) Planting density – an agricultural and economic appraisal of various planting strategies. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 223–244, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [9.3.3.2; 9.3.3.3]
- Rees A.R. (1958) Field observations of midday closure of stomata in the oil palm, *Elaeis guineensis* Jacq. *Nature*, **182**, 735–736 [4.3.3.2]
- Rees A.R. (1959) The germination of oil palm seed: the cooling effect. *J. W. Afr. Inst. Oil Palm Res.*, **3**, 76–82 [7.1.4.3]
- Rees A.R. (1960) Early development of the oil palm seedling. *Principes*, **4**, 148–150 [2.2.1.2]
- Rees A.R. (1961a) Effect of high-temperature pre-treatment on the germination of oil palm seed. *Nature*, **189**, 74–75 [7.1.1.2]
- Rees A.R. (1961b) Midday closure of stomata in the oil palm, *Elaeis guineensis* Jacq. *J. Exp. Bot.*, **12**, 129–146 [4.3.3.2; 4.3.4]
- Rees A.R. (1962a) Dry-matter production by evergreen perennials. *Nature*, **195**, 1118–1119 [4.1.1.1; 4.1.2.1]
- Rees A.R. (1962b) Some observations on the preparation and storage of oil palm seed. *J. W. Afr. Inst. Oil Palm Res.*, **3**, 329–338 [7.1.3.1, 7.1.4.4]
- Rees A.R. (1962c) High-temperature pre-treatment and the germination of seed of the oil palm, *Elaeis guineensis* (Jacq.). *Ann. Bot.*, **26**, 569–581 [7.1]
- Rees A.R. (1963a) Relationship between crop growth rate and leaf area index in the oil palm. *Nature*, **197**, 63–64 [4.3.5.2; 4.3.8.3]
- Rees A.R. (1963b) A note on the fate of oil palm seed in a number of habitats. *J. W. Afr. Inst. Oil Palm Res.*, **4**, 208–211 [7.1.2]
- Rees A.R. (1963c) A large-scale test of storage methods for oil palm seed. *J. W. Afr. Inst. Oil Palm Res.*, **4**, 46–51 [7.1.3.2]
- Rees A.R. (1963d) Some factors affecting the germination of oil palm seeds under natural conditions. *J. W. Afr. Inst. Oil Palm Res.*, **4**, 201–207 [7.1; 7.1.2]
- Rees A.R. (1963e) An analysis of growth of oil palms under nursery conditions. II. The effect of spacing and season on growth. *Ann. Bot.*, **27**, 615–626 [4.1.1.1]
- Rees A.R. (1963f) A note on the spines of the oil palm. *Principes*, **7**, 30–31 [2.2.1.4]
- Rees A.R. (1964) The apical organization and phyllotaxis of the oil palm. *Ann. Bot.*, **28**, 57–69 [2.2.1.3]
- Rees A.R. (1965a) Evidence for the African origin of the oil palm. *Principes*, **9**, 30–36 [1.1.2]
- Rees A.R. (1965b) Some factors affecting the viability of oil palm seed in storage. *J. Nigerian Inst. Oil Palm Res.*, **4**, 317–324 [7.1.3.2]
- Rees A.R. & Chapas L.C. (1963a) An analysis of growth of oil palms under nursery conditions. I Establishment and growth in the wet season. *Ann. Bot.*, **27**, 607–614 [4.1.1.1]
- Rees A.R. & Chapas L.C. (1963b) Water availability and consumptive use in oil palm nurseries. *J. W. Afr. Inst. Oil Palm Res.*, **13**, 52–65 [7.2.2.3]
- Rees A.R. & Tinker P.B. (1963) Dry-matter production and nutrient content of plantation oil palms in Nigeria. I. Growth and dry-matter production. *Pl. Soil*, **19**, 19–32 [4.1.1.1; 4.1.2]
- Renard J.L. (1970) La fusariose du palmier à huile. Role des blessures des racines dans le processus d'infection. *Oléagineux*, **25**, 581–586 [12.1.6.2]
- Renard J.L. (1981) *Le blast du palmier à huile – effet des traitements à la tetracycline*. Paper presented at Colloque International 'Protection des cultures tropicale', Lyon [12.1.4]

- Renard J.L. & de Franqueville H. (1989a) Oil palm bud rot. *Oléagineux*, **44**, 87–92 [12.1; 12.1.5.4]
- Renard J.L. & de Franqueville H. (1989b) Oil palm vascular wilt. *Oléagineux*, **44**, 341–349 [12.1.6.2]
- Renard J.L. & de Franqueville H. (1991) Effectiveness of crop techniques in the integrated control of oil palm vascular wilt. *Oléagineux*, **46**, 255–265 [9.1.4.1; 12.1.6.2]
- Renard J.L. & Quillec G. (1983) *Fusarium* and replanting. Elements to be considered when replanting oil palm in a *Fusarium* zone in West Africa. *Oléagineux*, **38**, 421–427 [12.1.6.2]
- Renard J.L., Gascon J.P. & Bachy A. (1972) Research on vascular wilt disease of the oil palm. *Oléagineux*, **27**, 581–591 [12.1.6.2]
- Renard J.L., Mariau D. & Quencez P. (1975) Le blast du palmier à huile: rôle des insectes dans la maladie. Résultats préliminaires. *Oléagineux*, **30**, 497–500 [12.1.4]
- Renard J.L., Noiret J.M. & Meunier J. (1980) Sources et gammes de résistance à la fusariose chez les palmiers à huile *Elaeis guineensis* et *Elaeis melanococca*. *Oléagineux*, **35**, 387–393 [12.1.6.2]
- Renard J.L., de Franqueville H., Meunier J. & Noiret J.M. (1991) Méthode d'évaluation du comportement du palmier à huile vis-à-vis de la fusariose vasculaire due à *Fusarium oxysporum* f.sp. *elaeidis* – résultats. In: *L'amélioration des plantes pour l'adaptation aux milieux arides* (Ed. by N. Chalbi & Y. Demarly), pp. 121–134, John Libbey Eurotext, Paris [12.1.6.2]
- Renard J.L., de Franqueville H., Diabaté S. & Ouvrier M. (1993) Study of the impact of vascular wilt on FFB production in oil palm. *Oléagineux*, **48**, 495–504 [5.3.5; 12.1.6.2]
- Rethinam P. (1998) Recent advances in oil palm cultivation in India. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 221–225, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.4.3.3]
- Rey H., Quencez P., Ochs R. & Olivin J. (1991) Soils study for the siting of an oil palm plantation. *Oléagineux*, **46**, 391–394 [8.1.3.3]
- Rey H., Quencez P., Dufrene E. & Dubos B. (1998) Oil palm water profiles and water supplies in Côte d'Ivoire. *Plantations, Recherche, Développement*, **5**, 47–57 [3.2.2.3; 10.3.1.2]
- Rhainds M. (2000) A review of recent sampling and ecological studies on bagworms (Lepidoptera: Psychidae) in commercial plantations of oil palm. *Planter, Kuala Lumpur*, **76**, 9–14 [12.2.1.4; 12.2.5.2]
- Richardson D.L. (1995) The history of oil palm breeding in the United Fruit Company. *ASD Oil Palm Papers*, **11**, 1–22 [5.1.4; 5.1.6.3; 5.1.7.2; 5.1.7.3]
- Rival A. (2000) Somatic embryogenesis in oil palm. In: *Somatic embryogenesis in woody plants* (Ed. by S.M. Jain, P.K. Gupta & R.J. Newton), pp. 249–289, Kluwer Academic, Dordrecht [6.2.1; 6.3.1.1; 6.4; 6.5.1; 6.5.3]
- Rival A., Bernard F. & Mathieu Y. (1997) Changes in peroxidase activity during *in vitro* rooting of oil palm (*Elaeis guineensis* Jacq.). *Sci. Hort.*, **71**, 103–112 [6.2.1; 6.2.1.3; 6.2.3]
- Rival A., Bertrand L., Beulé T., Combes M.C., Trouslot P. & Lashermes P. (1998a) Suitability of RAPD analysis for the detection of somaclonal variants in oil palm (*Elaeis guineensis* Jacq.). *Pl. Breed.*, **117**, 73–76 [6.3.1.2]
- Rival A., Tregear J., Verdeil J.L., Richaud F., Beulé T., Duval Y., Hartman C. & Rode A. (1998b) Molecular search for mRNA and genomic markers of the oil palm 'mantled' somaclonal variation. *Acta Hort.*, **461**, 165–171 [6.3.1.2; 6.3.3]
- Rival A., Triques K., Beulé T., Nato A., Lavergne D., Santamaria J., Verdeil J.L., Hoche V., Oropeza C. & Hamon S. (1999) A multi-parameter approach for the study of *in vitro* photosynthesis. In: *Plant biotechnology and in vitro biology in the 21st century* (Ed. by R. Altman *et al.*), pp. 437–440, Kluwer Academic, Dordrecht [6.2.3]
- Rival A., Jalignot E., Beulé T., Verdeil J.L. & Tregear J. (2000) DNA methylation and somaclonal variation in oil palm. In: *Proc. Int. Symp. 'Methods and markers for quality assurance in micropropagation'* (Ed. by A.C. Cassells), pp. 447–454, ISHS Commission on Biotechnology, Cork [6.3.1.2]
- Rival A., Tregear J., Jalignot E., Morcillo F., Aberlenc F., Billotte N., Richaud F., Beulé T., Borgel A. & Duval Y. (2001) Oil palm biotechnology at CIRAD. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 51–82, Malaysian Palm Oil Board, Kuala Lumpur [5.2.8.3; 6.3.3]
- Rivera C., Pereira R., Moreira L. & Chinchilla C. (1996) Detection of potyvirus-like particles associated with oil palms (*Elaeis guineensis*) in Ecuador. *Pl. Disease*, **80**, 1301 [12.1]
- Robertson G.W. & Foong S.F. (1977) Weather-based yield forecasts for oil palm fresh fruit bunches. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 695–709, Incomp. Soc. Planters, Kuala Lumpur [4.5.3; 4.5.4]
- Robertson J.S. (1956) Leaf diseases of oil palm seedlings. *J. W. Afr. Inst. Oil Palm Res.*, **1** (4), 110–122 [12.1; 12.1.2.1]
- Robertson J.S. (1959a) Blast disease of the oil palm: its cause, incidence and control in Nigeria. *J. W. Afr. Inst. Oil Palm Res.*, **2**, 310–330 [7.2.4; 12.1.4]
- Robertson J.S. (1959b) Co-infection by a species of *Pythium* and *Rhizoctonia lamellifera* Small in blast disease of oil palm seedlings. *Trans. Br. mycol. Soc.*, **42**, 401–405 [7.2.4; 12.1.4]
- Robertson J.S. (1960) Plant pathology division. In: *8th Annu. Rep. W. Afr. Inst. Oil Palm Res.*, pp. 106–112, Benin City [12.1.2.1; 12.1.7.1]
- Robertson J.S. (1962a) Investigations into an outbreak of dry basal rot at Akwukwu in western Nigeria. *J. W. Afr. Inst. Oil Palm Res.*, **3**, 339–343 [12.1.6.1]
- Robertson J.S. (1962b) Plant pathology division. In: *10th Annu. Rep. W. Afr. Inst. Oil Palm Res.*, pp. 78–83, Benin City [12.1.6.1]
- Robertson J.S. (1962c) Dry basal rot, a new disease of oil palms caused by *Ceratocystis paradoxa* (Dade) Moreau. *Trans. Br. mycol. Soc.*, **45**, 475–478 [12.1.6.1]
- Robertson J.S. (1963) Plant pathology division. In: *11th Annu. Rep. W. Afr. Inst. Oil Palm Res.*, pp. 77–82, Benin City [12.1.2.1]
- Robertson J.S., Prendergast A.G. & Sly J.M.A. (1968) Diseases, disorders and deficiency symptoms of the oil palm in West Africa. *J. Nigerian Inst. Oil Palm Res.*, **4**, 381–409 [12.1]
- Rodrigues M.R.L., Malavolta E. & Chaillard H. (1997) La fumure du palmier à huile en Amazonie centrale brésilienne. *Plantations, Recherche, Développement*, **4**, 392–398 [3.5.3; 11.3.3.2]
- Roege W., Velayuthan A. & Chan K.L. (1983) Experience with decanter for palm oil clarification. In: *Proc. Regional Workshop 'Palm oil mill technology and effluent treatment'*, pp. 85–91, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.3.6; 13.6.3]
- Rojas-Cruz L.A. (1977) Insect pests of oil palms in Colombia. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 666–671, Incomp. Soc. Planters, Kuala Lumpur [12.2.5.3]
- Rosenquist A. (1996) Evaluation of JERS-1, ERS-1 and Almaz

- SAR backscatter for rubber and oil palm stands in West Malaysia. *Int. J. Remote Sensing*, **17**, 3210–3231 [10.7.5]
- Rosenquist E.A. (1982) Performance of identical oil palm progenies in different environments. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 131–143, Incomp. Soc. Planters, Kuala Lumpur [5.5.1.7]
- Rosenquist E.A. (1986) The genetic base of oil palm breeding populations. In: *Proc. Int. Workshop 'Oil palm germplasm and utilisation'*, pp. 27–56, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1; 5.5.1.4]
- Rosenquist E.A. (1990) An overview of breeding technology and selection in *Elaeis guineensis*. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 5–25, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.2; 5.1.1.3; 5.1.5; 5.3.3.1; 5.4.2.1; 5.4.2.5]
- Rosenquist E.A. (1999) Some ancestral palms and their descendants. In: *Proc. Seminar 'Science of oil palm breeding'* (Montpellier, 1992) (Ed. by N. Rajanaidu & B.S. Jalani), pp. 8–36, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.2]
- Rosenquist E.A., Corley R.H.V. & de Greef W. (1990) Improvement of *tenera* populations using germplasm from breeding programmes in Cameroon and Zaire. In: *Proc. Workshop 'Progress of oil palm breeding populations'*, pp. 37–69, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.2; 5.1.3.2; 5.1.3.3; 5.1.6.1; 5.2.5; 5.3.4.1; 5.4.3; 12.1.6.2]
- Ruer P. (1963) Les préépipinières de palmiers à huile en sachets de polyéthylène. *Oléagineux*, **18**, 693–696 [7.2.5]
- Ruer P. (1967a) Répartition en surface du système racinaire du palmier à huile. *Oléagineux*, **22**, 535–537 [2.2.1.5; 4.3.8.3; 11.2.1.2; 11.2.1.3]
- Ruer P. (1967b) Morphologie et anatomie du système racinaire du palmier à huile. *Oléagineux*, **22**, 595–599 [2.2.1.5]
- Ruer P. (1968) *Contribution à l'étude du système racinaire du palmier à huile*. Thesis, University of Paris [2.2.1.5; 4.2.1.4]
- Ruer P. (1969) Système racinaire du palmier à huile et alimentation hydrique. *Oléagineux*, **24**, 327–330 [2.2.1.5]
- Ruer P. & Varechon C. (1964) Premières observations sur les caractéristiques du pétiole de la feuille de palmier à huile. *Oléagineux*, **19**, 539–542 [4.3.2.3]
- Ruiz Romero R. & Henson I.E. (2002) Photosynthesis and stomatal conductance of oil palm in Colombia: some initial observations. *Planter, Kuala Lumpur* **78**, 301–308 [4.3.3.2; 4.3.4]
- Russell E.W. (1973) *Soil conditions and plant growth*, 10th edn, Longman, London [11.3.1; 11.3.2.2]
- Russell T.B. (2000) Approach to mechanisation for the plantation sector: J.A. Russell Group's experience on tea plantations. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 653–658, Incomp. Soc. Planters, Kuala Lumpur [10.4.7]
- Sala O.E. and 18 others (2000) Global biodiversity and scenarios for the year 2100. *Science*, **287**, 1770–1774 [3.3.2]
- Salako F.K., Lal R. & Swift M.J. (1995) Intercropping oil palm (*Elais guineensis* Jacq.) with cocoyam (*Xanthosoma sagittifolius*) on windrow and non-windrow in southern Nigeria. *J. Sustainable Agr.*, **6**, 47–60 [3.4.3.10; 8.4.3.1]
- Salako F.K., Hauser S., Babalola O. & Tian G. (2001) Improvement of the physical fertility of a degraded alfisol with planted and natural fallows under humid tropical conditions. *Soil Use Manage.*, **17**, 41–47 [3.4.3.10; 8.4.3.2]
- Salleh A., Teng W.H. & Chan K.W. (1990) Economic evaluation of mechanised applications of the empty fruit bunches – Guthrie's experience. *Planter, Kuala Lumpur*, **66**, 179–189 [10.1.3.2]
- Salmiah A., Kang Y.B. & Mohtar Yusof (2000a) Basic oleochemicals. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 1141–1194, Malaysian Palm Oil Board, Kuala Lumpur [14.3.6.1]
- Salmiah A., Rosnah Ismail & Ooi T.L. (2000b) Oleochemical uses. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 1195–1292, Malaysian Palm Oil Board, Kuala Lumpur [14.3.6.1]
- Sambanthamurthi R., Oo K.C. & Parman S.H. (1995) Factors affecting lipase activity in *Elaeis guineensis* mesocarp. *Pl. Physiol. Biochem.*, **33**, 353–359 [5.5.1.6; 13.3.3]
- Sambanthamurthi R., Parman S.H. & Noor M.R.M. (1996) Oil palm (*Elaeis guineensis*) protoplasts: isolation, culture and microcallus formation. *Pl. Cell Tissue Organ Culture*, **46**, 35–41 [6.6.1.2]
- Sambanthamurthi R., Parveez G.K.A. & Cheah S.C. (2000a) Genetic engineering of the oil palm. In: *Advances in oil palm research*, Vol. 1 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 284–331, Malaysian Palm Oil Board, Kuala Lumpur [6.6.1.2; 6.6.2.1;]
- Sambanthamurthi R., Sundram K. & Tan Y.A. (2000b) Chemistry and biochemistry of palm oil. *Progr. Lipid Res.*, **39**, 507–558 [13.1.2; 13.3.3; 14.3.4; 14.3.6.1; 14.4]
- Sample E.C., Soper R.J. & Racz G.J. (1980) Reactions of phosphate fertilisers in soils. In: *The role of phosphorus in agriculture* (Ed. by F.E. Kwasaneh, E.C. Sample & E.J. Kamprath), pp. 263–310, Amer. Soc. Agron., Madison, WI [11.6.1.2]
- Samsudin A., Chew P.S. & Mat Min M. (1993) *Oryctes rhinoceros*: breeding and damage on oil palms in an oil palm to oil palm replanting situation. *Planter, Kuala Lumpur*, **69**, 583–591 [12.2.4.1]
- Sanchez P.A. (1976) *Properties and management of soils in the tropics*, Wiley, New York [3.4.1.2; 3.4.3.5; 3.4.3.9; 11.7.4.1; 11.8.1]
- Sanchez P.A. & Uehara G. (1980) Management considerations for acid soils with high phosphorus fixation capacity. In: *The role of phosphorus in agriculture* (Ed. by F.E. Kwasaneh, E.C. Sample & E.J. Kamprath), pp. 471–514, Amer. Soc. Agron., Madison, WI [11.9.3]
- Sanderson F.R. & Pilotti C.A. (1997) *The importance of spores in the epidemiology of Ganoderma*. Paper presented at Conf. Int. Soc. Oil Palm Agronomists, 1–2 Sept., Cartagena, Colombia [12.1.6.3]
- Sanderson F.R., Pilotti C.A. & Bridge P.D. (2000) Basidiospores: their influence on our thinking regarding a control strategy for basal stem rot of oil palm. In: *Ganoderma diseases of perennial crops* (Ed. by J. Flood, P.D. Bridge & M. Holderness), pp. 113–119, CABI Publishing, Wallingford [12.1.6.3]
- Santacruz L., Zambrano J., Avila M. & Calvo F. (2000) *El complejo pudrición de cogollo en la zona oriental de Colombia*. Paper presented at Conf. 'Competitividad y prospectiva de la palma de aceite', 6–8 Sept., Cartagena, Colombia [12.1.7.2]
- Santa Maria N., Rajah Padman C.V., Arikiyah A. & Amrik Singh D. (1996) The cambering–pulverising system in the replanting of oil palms. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 263–268, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.4.2]
- Sanyal S.K. & de Datta S.K. (1991) Chemistry of phosphorus transformations in soil. *Adv. Soil Sci.*, **16**, 1–120 [11.9.2.3]

- Sanz Veiga A. (1998) La industria de aceite de palma en Brasil. *Palmas (Bogota)*, **19** (Special no.), 81–84 [1.4.3.8]
- Sarakoon N. (1998) Palm oil industry Thailand. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 648–656, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.4.3.3]
- Sargeant H.J. (2001) *Oil palm agriculture in the wetlands of Sumatra: destruction or development?* European Union Ministry of Forestry, Brussels [1.4.3.1; 1.5.4; 3.3.2; 3.4.3.7; 8.3.6]
- Sariah M. & Zakaria K. (2000) The use of soil amendments for the control of basal stem rot of oil palm seedlings. In: *Ganoderma diseases of perennial crops* (Ed. by J. Flood, P.D. Bridge & M. Holderness), pp. 89–99, CABI Publishing, Wallingford [12.1.6.3]
- Sariah M., Hussin M.Z., Miller R.N.G. & Holderness M. (1994) Pathogenicity of *Ganoderma boninense* tested by inoculation of oil palm seedlings. *Pl. Pathol.*, **43**, 507–510 [12.1.6.3]
- Sarjit S. (1986) The use of electric drills for more efficient trunk injection against bagworm in oil palm. *Planter, Kuala Lumpur*, **62**, 54–57 [12.2.1.4; 12.2.5.2; 12.2.5.5]
- Sasaerila Y., Gries R., Gries G., Khaskin G., King S. & Boo T.C. (2000) Decadienoates: sex pheromone components of nettle caterpillars *Darna trima* and *D. bradleyi*. *J. Chem. Ecol.*, **26**, 1969–1981 [12.2.5.1]
- Schad H. (1914) Die geographische Verbreitung der Olpalme (*Elaeis guineensis*). *Tropenpflanzer*, **18**, 359–391, 447–462 [1.2.1]
- Schmidt A. (1986) Wild boar control with electric fences. *Oléagineux*, **41**, 557–562 [12.3.2]
- Schmöle J.F. (1930) The selection of oil palms (*Elaeis guineensis*) Jacq. In: *Proc. 4th Pacific Sci. Congr.*, 1929, Vol. 4, p. 185–190, Java [2.2; 5.1.1.1]
- Scholes R.J., Schulze E.D., Pitelka L.F. & Hall D.O. (1999) Biogeochemistry of terrestrial ecosystems. In: *The terrestrial biosphere and global change* (Ed. by B. Walker *et al.*), pp. 271–303, Cambridge University Press, Cambridge [3.3.2]
- Schroth G., Rodrigues M.R.L. & D'Angelo S.A. (2000) Spatial patterns of nitrogen mineralization, fertilizer distribution and roots explain nitrate leaching from mature Amazonian oil palm plantation. *Soil Use and Management*, **16**, 222–229 [11.2.1.3]
- Schuchardt F., Darnoko D. & Guritno P. (2002a) *Composting of empty oil palm fruit bunch (EFB) with simultaneous evaporation of oil mill waste water (POME)*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [10.1.3.2]
- Schuchardt F., Wilfert K. & Darnoko D. (2002b) *A new, integrated concept for combined waste (EFB) and waste water (POME) treatment in palm oil mills – technical, economical and ecological aspects*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [10.1.3.2]
- Schuiling M. & Dinther J.B.M. (1982) La maladie de l'anneau rouge a la plantation de palmiers à huile de Paricatuba, Para (Brésil): une étude de cas. *Oléagineux*, **37**, 555–563 [12.1.6.6]
- Schultz C., Ginting G., Moawad A., Mollers C., Pamin K., Subronto, Tahardi J.S. & Vlek P.L.G. (1998) The role of (vesicular-) arbuscular mycorrhiza in the weaning stage of micro-propagated oil plants. In: *Proc. BTIG Workshop 'Oil palm improvement through biotechnology'* (Ed. by J.S. Tahardi *et al.*), pp. 59–64, Biotechnology Research Unit for Estate Crops, Bogor, Indonesia [6.2.1.4]
- Schwitzer M.K. (1980) Non-food uses for palm oil. *Oléagineux*, **35**, 261–267 [1.6.2]
- Schwitzer M.K. (1985) Technical end uses of palm kernel and coconut oils. In: *'Palm kernel and coconut oils', Symp. Proc. No. 32*, pp. 42–51, British Food Manufacturing Industries Assoc., Leatherhead [14.3.6.1]
- Scott I.M. (1973) *Draft reclassification of the soils of Central and North Sarawak*. 2nd edn, Department of Agriculture, Sarawak, Kuching [3.4.1.3]
- Servant M. & Henry J. (1963) Détermination de la richesse en huile de la pulpe du fruit de palme. *Oléagineux*, **18**, 339–341 [5.2.4.2]
- Setiyo I.E., Subronto & Lamade E. (1996) Photosynthetic rate of three different D × P clones: the sensitivity to vapour pressure deficit in North Sumatra. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 421–426, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.3.8.2]
- Setyobudi H., Lihanaswan S. & Wanasuria S. (1998) Iron deficiency in mature oil palms in Riau, Sumatra. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 363–369, Indonesian Oil Palm Res. Inst., Medan, Indonesia [12.1.7.2]
- Shah F.H. & Cha T.S. (2000) A mesocarp and species-specific cDNA clone from oil palm encodes for sesquiterpene synthase. *Pl. Sci.*, **154**, 153–160 [6.6.2.2]
- Shah F.H. & Lim S.N. (1996) Use of microsatellites in the determination of genetic variation and genetic relationship between various oil palm populations. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 568–574, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [2.2]
- Shah F.H. & Mansor A. (1997) *Isolation and characterisation of cDNA encoding oil palm thioesterase genes*. Paper presented at Plant Molecular Biology Conf., Singapore [6.6.2.1]
- Shah F.H., Rashid O., Simons A.J. & Dunsdon A. (1994) The utility of RAPD markers for the determination of genetic variation in oil palm (*Elaeis guineensis*). *Theor. appl. Genet.*, **89**, 713–718 [5.2.8.2]
- Shahabudin S.A.J. (1993) The roles of KLCE and other related futures exchanges in the vegetable oils trade. In: *Proc. 1991 Int. Palm Oil Conf. – Promotion and marketing* (Ed. by Y. Basiron *et al.*), pp. 74–81, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.1.1]
- Shamsul Bahrin & Lee B.T. (1988) *Three decades of evolution*, Felda, Kuala Lumpur [1.5.3; 10.8.1.1]
- Sharifah S.S.A., Singh R. & Cheah S.C. (1999) Molecular dissection of the floral clonal abnormality in oil palm. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 321–329, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.3]
- Sharma M. (1998) *Palm age, bunch weight and its impact on OER*. Paper presented at Nat. Seminar 'Opportunity for maximising production through better OER and offshore investment in oil palm', Palm Oil Res. Inst. Malaysia, Kuala Lumpur. [10.5.2; 10.5.3]
- Sharma M. (1999) Utilization of Nigerian PS1 and PS2 selection in oil palm breeding programmes at UP Bhd. In: *Proc. Seminar 'PS1 and PS2 oil palm planting materials'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 18–29, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.3.4.1; 5.3.7.1]

- Sharma M. & Tan Y.P. (1990) Performance of the *Elaeis oleifera* × *Elaeis guineensis* (OG) hybrids and their backcrosses. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 40–43, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [2.4; 5.5.1.6]
- Sharma M. & Tan Y.P. (1997) Oil palm breeding programmes and the performance of D × P planting materials at United Plantations Berhad. *Planter, Kuala Lumpur*, 73, 591–610 [5.3.3.2; 5.3.7.1; 5.6]
- Sharma M., Tan Y.P. & Chai M. (1994) *Breeding oil palm for high iodine value oil*. Paper presented at Colloquium 'Oil palm genetic resources', 13 Sept., Palm Oil Res. Inst. Malaysia, Bangi, Malaysia [5.3.7.1]
- Sharma M., Gurmit S., Toh T.S. & Singh T. (1999) *Optimising on FFB, oil, OER and oil quality*. Paper presented at 1999 PORIM Int. Palm Oil Congr., 1–6 Feb., Kuala Lumpur [4.5.2; 5.2.4.2]
- Siburat S. & Mojiun P. (1998) Incidence of leaf-eating caterpillars and control in PPBOP, Sabah. *Planter, Kuala Lumpur*, 74, 421–433 [12.2.1.1]
- Sidhu M., Surianto & Sinuraya Z. (2000) Comparative evaluation of new fertiliser types for use in oil palm nurseries and young field plantings. *Planter, Kuala Lumpur*, 76, 537–562 [7.2.2.3]
- Sidhu M., Surianto & Sinuraya Z. (2001) Investigations into corrective treatment of micro-nutrient deficiency in a peat soil oil palm nursery. *Planter, Kuala Lumpur*, 77, 7–18 [11.8.5]
- Siew W.L. (2000a) Analysis of palm and palm kernel oils. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 895–934, Malaysian Palm Oil Board, Kuala Lumpur [13.1.1; 13.4.6; 14.3.1]
- Siew W.L. (2000b) Enhancement of oil quality. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 935–967, Malaysian Palm Oil Board, Kuala Lumpur [13.4.6; 14.3.2]
- Simon S., Hendry T., Chang S.W. & Kiaw C.W. (1998) Early yield performance of clonal oil palm (*Elaeis guineensis* Jacq.) plantings in PPB Oil Palms Bhd, Sabah – a case study. *Planter, Kuala Lumpur*, 74, 257–269 [6.5.3]
- Simon S., Domanic J., Michael A. & Chang S.W. (2001) An update of yield performance of clonal oil palm (*Elaeis guineensis* Jacq.) plantings in PPB Oil Palms Bhd, Sabah. In: *Strategic directions for the sustainability of the oil palm industry* (Ed. by E. Pushparajah), pp. 1–11, Incomp. Soc. Planters, Kuala Lumpur [6.5.3]
- Singh R.P., de Avila A.C., Dusi A.N., Boucher A., Trinidade D.R., van Slobbe W.G., Ribeiro S.G. & Fonseca M.E.N. (1988) Association of viroid-like nucleic acids with the fatal yellowing disease of oil palm. *Fitopatol. bras.*, 13, 392–394 [12.1.7.2]
- Sipayung A., Desmier de Chenon R. & Sudharto P.S. (1990) Recent work with viruses in the biological control of leaf eating caterpillars in North Sumatra, Indonesia. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 285–293, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.1.4]
- Siregar H.H., Darmosarkoro W. & Poeloengan Z. (1998) Oil palm yield simulation using drought characteristics. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 585–594, Indonesian Oil Palm Res. Inst., Medan, Indonesia [3.3.1; 8.1.5.3]
- Siregar F.A., Saletes S., Caliman J.P. & Liwang T. (2002) *Empty fruit bunch compost: processing and utilities*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [10.1.3.2]
- Sitepu B., Nelson S.P.C. & Caligari P.D.S. (2002) *Bunch number and bunch weight-choosing their optima*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [5.3.2; 10.4.6; 10.4.7]
- Siti Nor Akmar A., Shah F.H. & Cheah S.C. (1995) Construction of oil palm mesocarp cDNA library and the isolation of mesocarp-specific cDNA clones. *Asia-Pacific J. molec. Biol. Biotech.*, 3, 106–111 [6.6.2.2]
- Siti Nor Akmar A., Murphy D.J. & Cheah S.C. (1996) Isolation of mesocarp-specific cDNA clones from the oil palm by subtractive hybridisation. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 552–556, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.6.2.2]
- Siti Nor Akmar A., Sambanthamurthi R. & Parveez G.K.A. (2001) Genetic modification of oil palm for producing novel oils. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 18–30, Malaysian Palm Oil Board, Kuala Lumpur [6.6.2]
- Sivasothy K. & Rohaya M.H. (2000) Crushing and sterilising of fresh fruit bunches: a promising approach for continuous sterilisation. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 823–834, Incomp. Soc. Planters, Kuala Lumpur [13.4.3.2]
- Sly J.M.A. (1968) The results from pruning experiments on adult palms in Nigeria. *J. Nigerian Inst. Oil palm Res.*, 5, 89–99 [13.6.1.4]
- Sly J.M.A. & Chapas L.C. (1963) The effect of various spacings on the first 16 years of growth and production of the Nigerian oil palm under plantation conditions. *J. W. Afr. Inst. Oil Palm Res.*, 4, 31–45 [9.3.3; 9.3.4; 9.3.5]
- Sly J.M.A. & Sheldrick R.D. (1965) Agronomy division. In: *1st Annu. Rep. Nigerian Inst. Oil Palm Res.*, pp. 24–58, Benin City [9.1.4.1]
- Sly J.M.A. & Tinker P.B. (1962) An assessment of burning in the establishment of oil palm plantations in southern Nigeria. *Trop. Agric., Trinidad*, 39, 271–280 [8.3.2]
- Sly J.M.A., Sheldrick R.D. & Zeven A.C. (1963) Agronomy Division. In: *11th Annu. Rep. W. Afr. Inst. Oil Palm Res.*, pp. 24–58, Benin City [8.3.3.2; 10.1.4]
- Smal C. (1990) Research on the use of barn owls, *Tyto alba*, for biological control of rats in oil palm. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 342–356, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.3.1]
- Smaling E.M.A., Oenema O. & Fresco L.O. (Editors). (1999) *Nutrient disequilibria in agroecosystems – concepts and case studies*. CAB International, Wallingford [11.6.1.1]
- Smith B.G. (1989) The effects of soil water and atmospheric vapour pressure deficit on stomatal behaviour and photosynthesis in the oil palm. *J. exp. Bot.*, 40, 647–651 [4.3.3.2]
- Smith B.G. (1993a) Oil palm breeding – the potential for physiological selection criteria. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 57–62, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.1.4.3; 4.3.8.2; 5.2.7]
- Smith B.G. (1993b) Correlations between vegetative and yield characteristics and photosynthetic rate and stomatal conductance in the oil palm (*Elaeis guineensis* Jacq.). *Elaeis*, 5, 12–26 [4.3.8.2; 5.3.6.1]
- Smith B.G., Donough C.R. & Corley R.H.V. (1996) Relationship

- between oil palm clone phenotype and optimal planting density. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 76–86, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.4.4; 6.4.3.3; 9.3.2; 9.3.3.1; 9.3.5]
- Smith E.H.G. (1929) The oil palm (*Elaeis guineensis*) at Calabar. *Annu. Bull. Dept Agric., Nigeria*, 8, 5–42 [5.1.3.2]
- Smith E.H.G. (1935) A note on recent research on empire products (Extract from Botanical section Rep., S. Provinces, Nigeria, Jan.–June 1935). *Bull. imp. Inst., Lond.*, 33, 371 [2.2]
- Smith R.F. & Reynolds H.T. (1966) Principles, definitions and scope of integrated pest control. In: *Proc. FAO Symp. 'Integrated pest control'*, pp. 11–17, Food and Agriculture Organisation of the United Nations, Rome [12.2]
- Smith S.E. & Read D.J. (1997) *Mycorrhizal symbiosis*, Academic Press, San Diego, California [11.2.2]
- Smith W.K. & Thomas J.A. (1973) The isolation and *in vitro* cultivation of cells of *Elaeis guineensis*. *Oléagineux*, 28, 123–127 [6.2.1.1]
- Smyth A.J. & Dumanski J. (1993) *FESLM: an international framework for evaluating sustainable land management*, FAO World Soil Resources Report No. 73, FAO, Rome [8.1.5.4]
- Soepena H., Purba R.Y. & Pawirosukarto S. (2000) A control strategy for basal stem rot (*Ganoderma*) on oil palm. In: *Ganoderma diseases of perennial crops* (Ed. by J. Flood, P.D. Bridge & M. Holderness), pp. 83–88, CABI Publishing, Wallingford [12.1.6.3]
- Soh A.C. (1986) Expected yield increase with selected oil palm clones from current D × P seedling materials and its implications on clonal propagation, breeding and ortet selection. *Oléagineux*, 41, 51–56 [5.3.3.2; 5.5.2.1; 6.4.1; 6.5.3]
- Soh A.C. (1987) Current issues in oil palm breeding. *Malay. appl. Biol.*, 16, 101–108 [5.4.2; 5.4.2.1; 5.4.2.2]
- Soh A.C. (1994) Ranking parents by best linear unbiased prediction (BLUP) breeding values in oil palm. *Euphytica*, 76, 13–21 [5.4.2.4; 5.5.1.2]
- Soh A.C. (1998) Review of ortet selection in oil palm. *Planter, Kuala Lumpur*, 74, 217–226 [6.5.2]
- Soh A.C. (1999) Breeding plans and selection methods in oil palm. In: *Proc. Seminar 'Science of oil palm breeding'* (Montpellier, 1992) (Ed. by N. Rajanaidu & B.S. Jalani), pp. 65–95, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.4.2; 5.4.2.2]
- Soh A.C. & Chow C.S. (1989) Index selection in oil palm for cloning. In: *Proc. 6th Int. Congr. SABRAO*, pp. 713–716 [6.4.1]
- Soh A.C. & Chow C.S. (1993) Index selection utilizing plot and family information in oil palm. *Elaeis*, 5, 27–37 [5.3.2; 5.3.3.2; 5.3.4.1; 5.3.4.2; 5.4.1]
- Soh A.C., Vanialingam T., Taniputra B. & Pamin K. (1981) Derivatives of the Dumpy palm – some experimental results. *Planter, Kuala Lumpur*, 57, 227–239 [5.5.1.2; 5.5.1.4]
- Soh A.C., Lee C.H., Yong Y.Y., Chin C.W., Tan Y.P., Rajanaidu N. & Phuah P.K. (1990) The precision of oil palm breeding trials in Malaysia. In: *Int. Symp. 'Application of statistics to perennial tree crops research'* (Ed. by Soh A.C., N. Rajanaidu & M.N. Hasan Basri), pp. 41–50, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2.2; 11.3.2.3]
- Soh A.C., Chow C.S., Iyama S. & Yamada Y. (1994a) Candidate traits for index selection in choice of oil palm ortets for clonal propagation. *Euphytica*, 76, 23–32 [5.4.1]
- Soh A.C., Rajanaidu N. & Cheah S.C. (1994b) Oil palm breeding: the previous and the next 50 years. In: *'Management for enhanced profitability in plantations'* (Ed. by Chee K.H.), pp. 35–52, Incomp. Soc. Planters, Kuala Lumpur [6.6.2.1; 6.6.2.2]
- Soh A.C., Yong Y.Y., Ho Y.W. & Rajanaidu N. (1995) Commercial potential of oil palm clones: early results of their performance in several locations. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 134–144, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.4.2]
- Soh A.C., Wong G., Tan C.C., Chew P.S., Hor T.Y., Chong S.P. & Gopal K. (2001) Recent advances towards commercial production of elite oil palm clones. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 33–44, Malaysian Palm Oil Board, Kuala Lumpur [6.2.1.2; 6.4.2; 6.4.3.1; 6.5.1.1; 6.5.2]
- Sommer R., Denich M. & Vlek P.L.G. (2000) Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region, Brazil. *Pl. & Soil*, 219, 231–241 [11.2.1.3]
- Southworth A. (1976) Processing, storage and transport of palm oil and kernels. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 479–492, Elsevier, Amsterdam [13.4.3; 13.4.3.4; 13.4.3.5]
- Southworth A. (1977) Process control. In: *Proc. Int. Symp. 'Palm oil processing and marketing'*, Incomp. Soc. Planters, Kuala Lumpur [13.4.5.2]
- Southworth A. (1983) Oil extraction by pressing. In: *Proc. Regional Workshop 'Palm oil mill technology and effluent treatment'*, pp. 28–35, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.3.5]
- Sowunmi M.A. (1999) The significance of the oil palm (*Elaeis guineensis* Jacq.) in the late Holocene environments of west and west central Africa: a further consideration. *Veg. Hist. Archaeobotany*, 8, 199–210 [1.1.1]
- Sparnaaij L.D. (1955) Seedling selection in oil palm nurseries. *J. W. Afr. Inst. Oil Palm Res.*, 1, 51–63 [5.2.7; 7.2.2.4]
- Sparnaaij L.D. (1957) Mixed cropping in oil palm cultivation. *J. W. Afr. Inst. Oil Palm Res.*, 2, 244–264 [8.4.3.1]
- Sparnaaij L.D. (1958) The palmeries of the Kwango district. In: *Notes on a visit to research station, oil palm plantations and palmeries in the Belgian Congo, April 1958*, (Ed. by C.W.S. Hartley), Mimeographed report, W. Afr. Inst. Oil Palm Res., Benin, Nigeria [1.2.4]
- Sparnaaij L.D. (1960) The analysis of bunch production in the oil palm. *J. W. Afr. Inst. Oil Palm Res.*, 3, 109–180 [4.4; 4.4.4; 4.4.5; 4.4.6]
- Sparnaaij L.D. (1969) Oil palm – *Elaeis guineensis* Jacquin. In: *Outlines of perennial crop breeding in the tropics* (Ed. by F.P. Ferwerda & F. Wit), pp. 339–387, Veenman & Zonen, Wageningen [5.3.2; 5.3.3.1; 5.4.4]
- Sparnaaij L.D. & Gunn J.S. (1959) The development of transplanting techniques for the oil palm in West Africa. *J. W. Afr. Inst. Oil Palm Res.*, 2, 281–309 [9.1.4.2]
- Sparnaaij L.D. & van der Vossen H.A.M. (1980) Developments in oil palm breeding: a reappraisal of present and future breeding procedures in the light of results from the Nigerian Institute for Oil Palm Research breeding programme. *Oil Palm News*, 24, 4–11 [5.4.2.4]
- Sparnaaij L.D., Menendez T. & Blaak G. (1963a) Breeding and inheritance in the oil palm (*Elaeis guineensis* Jacq.). Part I. The

- design of a breeding programme. *J. W. Afr. Inst. Oil Palm Res.*, **4**, 126–155 [5.1.3.2; 5.3.3.1; 5.3.4.2; 5.4.2.1]
- Sparnaaij L.D., Rees A.R. & Chapas L.C. (1963b) Annual yield variation in the oil palm. *J. W. Afr. Inst. Oil Palm Res.*, **4**, 111–125 [4.4.4; 4.5.4]
- Speldewinde H.V. & Pereira J.R. (1974) Assisted pollination of oil palm in the Labuk valley, Sabah. *Planter, Kuala Lumpur*, **50**, 99–109 [4.4.7.1]
- Squire G.R. (1983) Solar energy and productivity in oil palm. In: *Annu. Res. Rep. Palm Oil Res. Inst. Malaysia 1983*, pp. 149–156 [4.1.1.2]
- Squire G.R. (1984a) Techniques in environmental physiology of oil palm: measurement of intercepted radiation. *Palm Oil Res. Inst. Malaysia, Bull.*, **8**, 10–13 [4.1.4.1; 4.1.4.2]
- Squire G.R. (1984b) *Light interception, productivity and yield of oil palm*. Internal report, Palm Oil Res. Inst. Malaysia [4.1.4.2; 4.1.4.4]
- Squire G.R. (1984c) Techniques in environmental physiology of oil palm: partitioning of rainfall above ground. *Palm Oil Res. Inst. Malaysia, Bull.*, **9**, 1–9 [3.2.2.1]
- Squire G.R. (1986) A physiological analysis for oil palm trials. *Palm Oil Res. Inst. Malaysia, Bull.*, **12**, 12–31 [4.1.1.2; 4.1.4.3; 4.1.4.4; 4.2.2; 4.3.2]
- Squire G.R. (1990) *The physiology of tropical crop production*, CAB International, Wallingford [4.2; 4.3.2.2]
- Squire G.R. & Corley R.H.V. (1987) Oil palm. In: *Tree crop physiology* (Ed. by M.R. Sethuraj & A.S. Raghavendra), pp. 141–167, Elsevier, Amsterdam [4.1.4.2; 4.1.4.3; 4.2.2; 4.3.1.2; 4.3.5; 4.3.8.1; 10.1.2.4]
- Sterling F. & Alvarado A. (1995) Ekona and Calabar as alternative sources of male parents in the commercial production of the oil palm seed. *ASD Oil Palm Papers*, **11**, 23–32 [5.1.3.3; 5.1.6.3; 5.5.1.2]
- Sterling F., Richardson D.L. & Chavez C. (1988) Some phenotypic characteristics of the descendants of 'QB49:238', an exceptional hybrid of oil palm. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 94–102, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.4.1; 5.5.1.6]
- Sterling F., Richardson D.L. & Chaves C. (1993) Honeycomb and randomised block designs for selection among oil palm (*Elaeis guineensis* Jacq) progenies. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 48–54, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.2.2]
- Steyaert R.L. (1967) Considérations générales sur le genre *Ganoderma* et plus spécialement sur les espèces Européennes. *Bull. Soc. Roy. Bot. Belg.*, **100**, 189–211 [12.1.6.3]
- Stilliard N.H. (1938) *The rise and development of legitimate trade in palm oil with West Africa*. Thesis, University of Birmingham [1.2.3]
- Stimpson K.M.S. & Rasmussen A.N. (1973) Clearing the old stand and some preparations for replanting coastal oil palms. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), p. 116–132, Incorp. Soc. Planters, Kuala Lumpur [12.1.6.3]
- Stoffels E. (1934) Contribution à l'étude de la sélection d'*Elaeis guineensis* à Sumatra. *Rev. Bot. appl. Agric. trop.*, **14**, 93–101 [5.1.1.1]
- Stringfellow R. (1999) Technological change in the vegetable oil market: is palm oil being left behind? *Oilseeds, oils and meals*, LMC International, Oxford, April, 1–6 [1.4.1; 1.5.4; 10.2; 10.4.5]
- Stringfellow R. (2000) The competitiveness of the palm oil industry now and in the future. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 199–214, Incorp. Soc. Planters, Kuala Lumpur [1.4.2.4; 11.3.2.3; 14.2]
- Subronto, Maskuddin & Pamin K. (1991) Efisiensi pengalihan energi pada tanaman kelapa sawit. *Buletin Perkebunan*, **22**, 33–49 [4.3.1.2; 4.3.2.2]
- Sudharto P., Sipayung A. & Desmier de Chenon R. (1993) Termites, a new problem on oil palm plantations in Indonesia. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 407–417, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.2]
- Sugih W., Heru S., Achmad F. & Thiagarajan S. (1996) Influence of rainfall, palm age and assisted pollination on oil palm fruit-set in Riau, Indonesia. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 207–220, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.4.1]
- Summugam R. (2000) Mechanisation in the oil palm plantation: problems and practices. *Planter, Kuala Lumpur*, **76**, 495–507 [10.2.2; 10.4.6]
- Sundaesan A., Arumughan C., Prasad K.V.S.V., Damodaran A.D. & Nampoothiri K.U.K. (1990) Design of indigenous small scale edible palm oil extraction unit. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Chemistry, technology, marketing*, pp. 81–88, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.4; 13.4.5.2]
- Sundram K. & Chandrasekharan N. (2000) Nutritional properties of palm oil and its components. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 1061–1101, Malaysian Palm Oil Board, Kuala Lumpur [13.1.4.1]
- Sunitha S. & Varghese P.T. (1999) Composting of oil palm wastes for efficient recycling of nutrients in palm plantations. *Planter, Kuala Lumpur*, **75**, 677–681 [11.7.2.1]
- Surre C. (1955) Densité économique de plantation pour le palmier à huile. *Oléagineux*, **10**, 411–413 [9.3.3.2; 9.3.3.3]
- Surre C. (1968) Les besoins en eau du palmier à huile. *Oléagineux*, **23**, 165–167 [3.2.2.2; 3.2.2.3; 10.3.1.1]
- Swinburne T.R. (1990) Amarillamiento fatal, pudrición de cogollo y pudrición de flecha de la palma africana. *Palmas (Bogota)*, **11** (4), 61–68 [12.1.7.2]
- Swinburne T.R. (1993) Fatal yellows, bud rot and spear rot of African oil palm – a comparison of the symptoms of these diseases in Brazil, Ecuador and Colombia. *Planter, Kuala Lumpur*, **69**, 15–23 [12.1.7.2]
- Swinburne T.R., Idris A.S., Watt T. & Ariffin D. (1998) *Basal stem rot of oil palm in Malaysia: factors associated with variation in disease severity*. Paper presented at Int. Workshop 'Ganoderma diseases', 5–8 Oct., Malay. Agric. Res. Dev. Inst., Serdang, Malaysia [12.1.6.3]
- Syed R.A. (1978) Bionomics of the three important species of bagworms on oil palm. *Malaysian agric. J.*, **51**, 392–398 [12.2.5.2]
- Syed R.A. (1979) Studies on oil palm pollination by insects. *Bull. ent. Res.*, **69**, 213–224 [2.2.2.5; 4.4.7.1]
- Syed R.A. (1982) Insect pollination of oil palm: feasibility of

- introducing *Elaeidobius* spp. into Malaysia. In: *The oil palm in agriculture in the eighties*, Vol. 1 (Ed. by E. Pushparajah & Chew P.S.), pp. 263–290, Incomp. Soc. Planters, Kuala Lumpur [2.2.2.5; 4.5.2; 10.4.1]
- Syed R.A. (1984) Los insectos polinizadores de la palma africana. *Palmas (Bogota)*, 5 (3), 19–87 [2.2.2.5]
- Syed R.A. & Saleh A. (1988) Population of *Elaeidobius kamerunicus* Fst. in relation to fruit set. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 528–534, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.4.7.1]
- Syed R.A. & Saleh A. (1993) Management of insect pests of oil palm in PTTP London Sumatra Indonesia plantations in Sumatra, Indonesia. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture* (Ed. by Y. Basiron *et al.*), pp. 451–457, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.2.5.1; 12.2.5.2]
- Syed R.A. & Saleh H.A. (1998) Integrated pest management of bagworms in oil palm plantations of PTTP London Sumatra Indonesia TBK (with particular reference to *Mahasena corbetti* Tams) in North Sumatra. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 386–391, Indonesian Oil Palm Res. Inst., Medan, Indonesia [12.2.5.2]
- Syed R.A. & Shah S. (1977) Some important aspects of insect pest management in oil palm estates in Sabah, Malaysia. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 577–590, Incomp. Soc. Planters, Kuala Lumpur [12.2.1.1]
- Syed R.A., Shah S. & Liew K.T. (1973) Occurrence and control of *Mahasena corbetti* Tams in oil palm estates in Sabah, Malaysia. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 402–413, Incomp. Soc. Planters, Kuala Lumpur [12.2.5.2]
- Syed R.A., Law I.H. & Corley R.H.V. (1982) Insect pollination of oil palm: introduction, establishment and pollinating efficiency of *Elaeidobius kamerunicus* in Malaysia. *Planter, Kuala Lumpur*, 58, 547–561 [2.2.2.5; 4.4.7.1]
- Sys C. (1960) Carte des sols du Congo Belge et du Ruanda-Urundi. *Pub. Inst. Nat. Etude agron. Congo Belge, Hors Ser.*, [3.5.2.3]
- Sys C., Verheyde W. & Paramanathan S. (1977) Evaluation of physical land characteristics in a tropical environment. In: *Proc. CLAMATROPS Conf. 'Classification and management of tropical soils'*, pp. 553–556, Malaysian Soc. Soil Sci., Kuala Lumpur [8.1.5.1]
- Szaro R. & Johnson D. (1996) *Biodiversity in managed landscapes, theory and practice*, Oxford University Press, New York [1.5.4; 8.2.1; 15.3.5]
- Tahardi J.S. (1998) Improvement of oil palm somatic embryogenesis by periodic immersion in liquid medium. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 595–601, Indonesian Oil Palm Res. Inst., Medan, Indonesia [6.5.1.1]
- Taib Y.M. (1985) Stochastic model for Malaysian palm oil production. *Palm Oil Res. Inst. Malaysia, Bull.*, 10, 25–28 [4.5.4]
- Tailliez B. (1969) Le désherbage selectif des préépinières de palmier à huile. *Oléagineux*, 24, 541–542 [7.2.1.2]
- Tailliez B. (1970) Germination accélérée des graines de palmier à huile. Technique avec substrat. *Oléagineux*, 25, 335–336 [7.1.4.2]
- Tailliez B. (1971) The root system of the oil palm on the San Alberto plantation in Colombia. *Oléagineux*, 26, 435–448 [2.2.1.5; 3.2.2.2; 4.1.2.3]
- Tailliez B. & Ballo Koffi C. (1992) A method for measuring oil palm leaf area. *Oléagineux*, 47, 537–545 [4.1.3.1]
- Tailliez B. & Valverde G. (1971) Sensitivity to hurricanes of different types of oil palm crosses. *Oléagineux*, 12, 753–762 [5.3.4.3]
- Taiwo O.E. & Osinowo F.A.O. (2001) Evaluation of various agro-wastes for traditional black soap production. *Bioresource Technol.*, 79, 95–97 [13.6.1.4]
- Tam T.K. (1973) Culling and selection in oil palm nurseries. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 104–113, Incomp. Soc. Planters, Kuala Lumpur [7.2.2.4]
- Tam T.K. (1981) Investigations into fruit-set capacities of the *Elaeis oleifera* under controlled pollination conditions and germination requirements of the interspecific *Elaeis oleifera* × *Elaeis guineensis* (pisifera) hybrid. *Planter, Kuala Lumpur*, 57, 444–451 [2.3.2; 7.1.4.6]
- Tam T.K., Lim C.S., Yeoh G.H. & Ooi S.C. (1977) The oil and other characteristics of interspecific (*Elaeis guineensis* × *Elaeis oleifera*) hybrids planted in Malaysia and their significance for future breeding programmes. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 27–38, Incomp. Soc. Planters, Kuala Lumpur [5.5.1.6]
- Tampubolon F.H., Daniel C. & Ochs R. (1990) Oil palm responses to nitrogen and phosphate fertiliser in Sumatra. *Oléagineux*, 45, 475–486 [11.3.3.1; 11.4.4.2; 11.6.3]
- Tan B.T. (1988) Cost of production of oil palm in major producing countries. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 339–354, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.4.2.4; 1.4.3.2; 11.9.2.1]
- Tan C.C., Wong G. & Soh A.C. (1999) *Acclimatisation and handling of oil palm tissue cultured plantlets for large scale commercial production*. Paper presented at 1999 PORIM Int. Palm Oil Congr., 1–6 Feb., Kuala Lumpur [6.2.1.3; 6.3.2]
- Tan G.Y. (1976) Cytology and cytogenetics. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 145–153, Elsevier, Amsterdam [2.2.1.6]
- Tan G.Y. (1978) Genetic studies of some morphophysiological characters associated with yield in oil palm (*Elaeis guineensis* Jacq.). *Trop. Agric., Trinidad*, 55, 9–16 [5.3.4.1]
- Tan G.Y. & Hardon J.J. (1976) Nursery selection. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 139–143, Elsevier, Amsterdam [2.2.1.2; 5.2.7]
- Tan G.Y. & Rajaratnam J.A. (1978) Genetic variability of leaf nutrient concentration in oil palm. *Crop Sci.*, 18, 548–550 [11.3.3.2; 11.4.4.2]
- Tan K.S. (1979) Root development of oil palms on inland soils of West Malaysia. In: *Soil physical properties and crop production in the tropics* (Ed. by R. Lal & D.J. Greenland), pp. 363–374, John Wiley & Sons, New York [2.2.1.5; 3.4.3.5; 4.1.2.3; 11.2.1.2]
- Tan K.S. & Ng W.C. (1982) Preliminary results of nutrient cycling of covers in oil palm on inland soils. In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 253–276, Incomp. Soc. Planters, Kuala Lumpur [10.1.3.1; 11.6.2.6]
- Tan K.S. & Rao A.N. (1979) Certain aspects of developmental morphology and anatomy of oil palm. In: *Histochemistry, devel-*

- opmental and structural anatomy of Angiosperms: a symposium, pp. 267–285 [2.2.2.3]
- Tan Y.P. (1975) Early yield benefits in oil palm from improved agronomic practices. *Perak Planters' Assoc. J.*, 1975, 51–56 [7.2.2.4]
- Tan Y.P. (1985) Weevil pollination in the *Elaeis oleifera* × *Elaeis guineensis* hybrid. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 34–40, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [2.4]
- Tan Y.P. & Basri Wahid M. (1985) Another pollinating insect of oil palm – *Pyroderces*. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 50–57, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [2.2.2.5]
- Tan Y.P. & Mohan E. (1982) Optimum depth of sowing and transplanting in the oil palm nursery. In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 415–424, Incomp. Soc. Planters, Kuala Lumpur [7.2.1.1, 7.2.2.1]
- Tan Y.P. & Ng S.K. (1977) Spacing for oil palms on coastal clays in Peninsular Malaysia. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 183–191, Incomp. Soc. Planters, Kuala Lumpur [9.3.3.1; 9.3.3.3]
- Tan Y.P., Ho Y.W. & Sharma M. (1996) Truncated leaf symptoms (TLS) on clonal seedlings. *Int. Soc. Oil Palm Breeders Newslett.*, 12 (1), 1–5 [6.3.2]
- Tandon R., Manohara T.N., Nijalingappa B.H.M. & Shivanna K.R. (2001) Pollination and pollen–pistil interaction in oil palm, *Elaeis guineensis*. *Ann. Bot.*, 87, 831–838 [2.2.2.2]
- Tang M.K., Nazeeb M. & Loong S.G. (1999) An insight into fertiliser types and application methods in Malaysian oil palm plantations. *Planter, Kuala Lumpur*, 75, 115–137 [11.9.2.1]
- Tang T.L. (1971) The possible use of *pisifera* in plantation. *Malay. agric. J.*, 48, 57–68 [5.5.1.5]
- Tang T.S. (2000) Composition and properties of palm oil products. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 845–894, Malaysian Palm Oil Board, Kuala Lumpur [13.1.2; 13.1.3; 13.1.4.2; 13.2.2; 14.3.1]
- Taniputra B., Lubis A.U., Pamin K. & Suheimi Syukur (1988) Progress of oil palm industry in Indonesia in the last fifteen years (1971–1985). In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 27–35, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [1.4.3.1]
- Tardieu F. (1993) Will progress in understanding soil–root relations and root signalling substantially alter water flux models? *Phil. Trans. Roy. Soc., Lond.*, 341, 56–66 [4.3.3.2]
- Tarmizi Mohamad A. (2000) Nutritional requirements and efficiency of fertiliser use in Malaysian oil palm cultivation. In: *Advances in oil palm research*, Vol. I (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 411–440, Malaysian Palm Oil Board, Kuala Lumpur [11.3.3.2]
- Tarmizi A.H. & Marziah M. (1995) The influence of low temperature treatment on growth and proline accumulation in polyembryogenic cultures of oil palm (*Elaeis guineensis* Jacq.). *Elaeis*, 7, 107–117 [4.4.5.4; 6.2.2.2]
- Tarmizi A.H., Collin H.A. & Hardwick K. (1999) Morphological variation in oil palm (*Elaeis guineensis* Jacq.) cultures. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 510–528, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.2]
- Taryo-Adiwiganda Y. & Poeloengan Z. (1998) General oil palm fertiliser recommendation in Indonesia: twenty-five years experience. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 325–334, Indonesian Oil Palm Res. Inst., Medan, Indonesia [11.3.3.2]
- Tayeb Dolmat M. (2000) Development and management of oil palm plantations. In: *Advances in oil palm research, Vol. I*, (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 441–465, Malaysian Palm Oil Board, Kuala Lumpur [8.3.1; 8.3.5; 11.8.1]
- Tayeb Dolmat M. & Hamdan A.B. (1999) Relation of fertiliser nutrients to *Ganoderma*. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 422–453, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.8.4; 12.1.6.3]
- Tayeb Dolmat M. & Tarmizi Mohamad A. (2001) Pragmatic manuring strategies amidst depressed palm oil prices. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 313–324, Malaysian Palm Oil Board, Kuala Lumpur [1.4.2.4; 11.2.3.2]
- Tayeb Dolmat M., Lim K.H., Zin Z.Z. & Halim Hassan A. (1988) Recent studies on the effects of land application of palm oil mill effluent on oil palm and the environment. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 596–604, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.2.1]
- Tayeb Dolmat M., Hamdan A.B. & Zulkifli H. (1995) Novel agromonic innovations in the exploitation of peat for oil palm. In: *Proc. 1993 PORIM Int. Palm Oil Congr. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 360–372, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.3.1.3; 8.3.6]
- Tayeb Dolmat M., Hamdan A.B., Zulkifli H. & Ahmad Tarmizi M. (1996) Fertiliser requirement of oil palm on peat – an update. In: *Proc. 1996 PORIM Int. Palm Oil Congr. 'Competitiveness for the 21st century'* (Ed. by D. Ariffin *et al.*), pp. 131–142, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.4.3.7; 8.3.1; 8.3.6; 11.3.3.2; 11.8.4]
- Teh C.L. (1996) Integrated pest management of leaf-eating caterpillars of oil palms in Sabah. *Planter, Kuala Lumpur*, 72, 395–405 [12.2.1]
- Teisson C., Alvard D., Berthouly M., Cote F., Escalant J.V. & Etienne H. (1995) *In vitro* culture by temporary immersion: a new device. *Plantations, Recherche, Développement*, 2 (5), 29–33 [6.5.1.1]
- Teixeira J.B., Sondahl M.R. & Kirby E.G. (1990) *Establishment of embryogenic cell suspensions of oil palm and regeneration*. Paper presented at Int. Assoc. Plant Tissue Culture Congress, June, Amsterdam [6.5.1.1]
- Teixeira J.B., Sondahl M.R. & Kirby E.G. (1993) Somatic embryogenesis from immature zygotic embryos of oil palm. *Pl. Cell Tissue Organ Culture*, 34, 227–233 [6.2.1]
- Teixeira J.B., Sondahl M.R. & Kirby E.G. (1994) Somatic embryogenesis from immature inflorescences of oil palm. *Pl. Cell Rep.*, 13, 247–250 [6.2.1.1]
- Teixeira J.B., Sondahl M.R., Nakamura T. & Kirby E.G. (1995) Establishment of oil palm cell suspensions and plant regeneration. *Pl. Cell Tissue Organ Culture*, 40, 105–111 [6.5.1.1]
- Teo C.B., Chew P.S., Goh K.J. & Kee K.K. (1998) Optimizing return from fertilizer for oil palms: an integrated agronomic approach. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 335–346, Indonesian Oil Palm Res. Inst., Medan, Indonesia [3.4.3.10; 11.9.2.1]
- Teo L. (1999) Mechanisation in oil palm plantation: some practi-

- cal considerations. *Planter, Kuala Lumpur*, 75, 233–243 [8.2.2; 10.2.1]
- Teo L. (2001) Should we continue to expand oil palm cultivation? *Planter, Kuala Lumpur*, 77, 63–64 [1.4.3.2]
- Teo L., Ong K.P. & MacLean R.J. (1990) Responses of oil palm to eradication of *Ischaemum muticum*. In: *Proc. 1989 PORIM Int. Palm Oil Dev. Conf.* (Ed. by B.S. Jalani *et al.*), pp. 301–307, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.6.2.6]
- Teo L., Ong K.P. & Zainuriah A. (2000) Effects of fertiliser withdrawal prior to replanting on oil palm performance. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 233–249, Incomp. Soc. Planters, Kuala Lumpur [8.3.4.2; 8.3.4.3; 11.3.2.3; 11.7.1]
- Teoh C.H., Ng A., Prudente C., Pang C. & Yee J.T.C. (2001) Balancing the need for sustainable oil palm development and conservation: the lower Kinabatangan floodplains experience. In: *Strategic directions for the sustainability of the oil palm industry* (Ed. by E. Pushparajah), pp. 1–25, Incomp. Soc. Planters, Kuala Lumpur [12.1.9]
- Teoh K.C. & Chew P.S. (1980) Fertiliser responses of oil palms on coastal clay soils in Peninsular Malaysia. In: *Proc. Conf. 'Soil science and agricultural development in Malaysia'* (Ed. by E. Pushparajah), pp. 191–212, Malaysian Soc. Soil Sci., Kuala Lumpur [10.1.2.2; 10.1.2.3]
- Teoh K.C. & Chew P.S. (1985) Investigation on areas and frequencies of fertiliser application in mature oil palms. In: *Proc. Int. Conf. 'Soils and plant nutrition'* (Ed. by A.T. Babchick & E. Pushparajah), pp. 357–387, Malaysian Soc. Soil Sci., Kuala Lumpur [11.7.4.1; 11.9.3]
- Teoh K.C. & Chew P.S. (1988a) Use of rachis analysis as an indicator of K nutrient status in oil palm. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 262–271, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.3.4.2; 11.4.2.2]
- Teoh K.C. & Chew P.S. (1988b) Potassium in the oil palm ecosystem and some implications to manuring practice. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 277–286, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.1.3.1; 11.1.4; 11.4.2.2; 11.4.3; 11.4.5.1; 11.6.1.1; 11.6.1.3; 11.6.1.4; 11.6.2.2; 11.6.2.6; 11.7.1]
- Tey C.C. & Ho C.T. (1995) Infection of *Oryctes rhinoceros* L. by application of *Metarhizium anisopliae* (Metsch.) Sorokin to breeding sites. *Planter, Kuala Lumpur*, 71, 563–567 [12.2.4.1]
- Tey S.H. & Chew P.S. (1997) GIS and GPS technologies for plantation crops. In: *Plantation management for the 21st century* (Ed. by E. Pushparajah), pp. 47–60, Incomp. Soc. Planters, Kuala Lumpur [8.2.1; 10.2.1]
- Tey S.H., Goh K.J. & Chew P.S. (2000) Digital elevation model (DEM) for site specific management in plantation crops. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 739–754, Incomp. Soc. Planters, Kuala Lumpur [8.2.1]
- Thambirajah J.J., Zulkali M.D. & Hashim M.A. (1995) Micro-biological and biochemical changes during the composting of oil palm empty fruit bunches – effect of nitrogen supplementation on the substrate. *Bioresource Technol.*, 52, 133–144 [11.7.2.1]
- Thomas R.L., Chan K.W. & Easau P.T. (1969a) Phyllotaxis in the oil palm: arrangement of fronds on the trunk of mature palms. *Ann. Bot.*, 33, 1001–1008 [2.2.1.3]
- Thomas R.L., Watson I. & Hardon J.J. (1969b) Inheritance of some components of yield in the 'Deli dura variety' of oil palm. *Euphytica*, 18, 92–100 [5.1.7.5; 5.3.2]
- Thomas R.L., Chan K.W. & Ng S.C. (1970) Phyllotaxis in the oil palm: arrangement of male/female spikelets on the inflorescence stalk. *Ann. Bot.*, 34, 93–105 [2.2.2.1]
- Thomas R.L., Phang S., Mok C.K., Chan K.W., Easau P.T. & Ng S.C. (1971) Fruit ripening in the oil palm *Elaeis guineensis*. *Ann. Bot.*, 35, 1219–1225 [13.3.2]
- Thomas R.L., Seth A.K., Chan K.W. & Ooi S.C. (1973) Induced parthenocarpy in the oil palm. *Ann. Bot.*, 37, 447–452 [2.2.2.7; 4.4.7.1]
- Thompson A. (1934) Chapter 7. In: *The oil palm in Malaya* (Ed. by B. Bunting, C.D.V. Georgi & J.N. Milsum), Dept Agric. Malaya, Kuala Lumpur [12.1.5.1; 12.1.8]
- Thompson A. (1936) *Ustilina zonata* on the oil palm. *Malay. agric. J.*, 34, 222–226 [12.1]
- Thompson A. (1937) *Observations on stem rot of the oil palm*. Dept Agric., Malaya, Sci. Ser. No. 21, Kuala Lumpur [12.1.6.5]
- Timms R.E. (1990) Crystallisation behaviour of palm oil. In: *Proc. Symp. 'New developments in palm oil'* (Ed. by K.G. Berger), pp. 38–44, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.3.1; 14.3.4]
- Timti I.N. (1991) Control of *Coelaenomenodera minuta* Uhlmann with *Crematogaster* species. *Trop. Pest Manage.*, 37, 403–408 [12.2.5.5]
- Tinker P.B. (1959) Soil heterogeneity and sampling procedure under oil palms. *J. W. Afr. Inst. Oil Palm Res.*, 3, 7–15 [3.2.2.1; 11.5.1; 11.7.5]
- Tinker P.B. (1961) Soil Chemistry Division. In: *9th Ann. Rep. W. Afr. Inst. Oil Palm Res.*, pp. 101–107, Benin, Nigeria [11.5.1]
- Tinker P.B. (1962) Some basement complex soils of Calabar Province, Eastern Nigeria. *J. W. Afr. Inst. Oil Palm Res.*, 3, 308–328 [3.5.2.2]
- Tinker P.B. (1963) Changes occurring in the sedimentary soils of southern Nigeria after oil palm plantation establishment. *J. W. Afr. Inst. Oil Palm Res.*, 4, 66–81 [8.4.3.1]
- Tinker P.B. (1964a) Studies on soil potassium. III. Cation activity ratios in acid Nigerian soils. *J. Soil Sci.*, 15, 24–34 [11.5.1]
- Tinker P.B. (1964b) Studies on soil potassium. IV. Equilibrium cation activity ratios and responses to potassium fertilizer of Nigerian oil palms. *J. Soil Sci.*, 15, 35–41 [11.5.1; 11.6.4.5]
- Tinker P.B. (1973) Potassium uptake rates in tropical crops. In: *Proc. 10th Coll. Int. Potash Inst.*, pp. 169–175, Abidjan [11.2.3]
- Tinker P.B. (1976) Soil requirements of the oil palm. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 165–181, Elsevier, Amsterdam [2.2.1.5; 3.2.2.2; 3.5.2.1; 11.2.1.1; 11.2.1.2; 11.2.1.3; 11.2.3]
- Tinker P.B. (1984) Site-specific yield potentials in relation to fertiliser use. In: *Nutrient balances and fertiliser needs in temperate agriculture* (Ed. by A. von Peter), pp. 193–208, 18th Coll. Int. Potash Inst., Bern [10.7.1; 10.7.2; 10.7.3]
- Tinker P.B. (1986) Trace elements in arable agriculture. *J. Soil Sci.*, 37, 587–601 [11.6.1.1]
- Tinker P.B. (1997) The environmental implications of intensified land use in developing countries. *Phil. Trans. Roy. Soc., Lond., B*, 352, 1023–1033 [3.3.2; 15.3.1]
- Tinker P.B. (2000a) The future research requirements for the oil palm plantation. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 3–40, Incomp. Soc. Planters, Kuala Lumpur

- [1.4.2.4; 1.4.3.2; 1.5.4; 5.6; 6.6.3; 8.3.4.1; 10.4.7; 10.6.2; 11.7.1; 15.1; 15.3.2]
- Tinker P.B. (2000b) *Shades of green – a review of UK farming systems*. Royal Agricultural Society of England, Stoneleigh Park, U.K. [1.6.2]
- Tinker P.B. (2001) *Organic farming – nutrient management and productivity*. Paper presented at International Fertiliser Society symposium, Lisbon, 5th March. [11.3.2.3]
- Tinker P.B. & Leigh R.A. (1985) Nutrient uptake by plants – efficiency and control. In: *Proc. Int. Conf. 'Soils and nutrition for perennial crops'* (Ed. by E. Pushparajah), pp. 3–17, Kuala Lumpur [11.4.2.2; 11.4.5.2]
- Tinker P.B. & Nye P.H. (2000) *Solute movement in the rhizosphere*, Oxford University Press, Oxford [2; 3; 4; 10; 11]
- Tinker P.B. & Smilde K.W. (1963a) Cation relationships and magnesium deficiency in the oil palm. *J. W. Afr. Inst. Oil Palm Res.*, **4**, 82–100 [8.1.3.6; 11.5.1; 11.9.2.2]
- Tinker P.B. & Smilde K.W. (1963b) Dry-matter production and nutrient content of plantation oil palms in Nigeria. II. Nutrient content. *Pl. Soil*, **19**, 350–363 [11.1.4; 11.4.2.2]
- Tinker P.B. & Ziboh C.O. (1959a) A study of some typical soils supporting oil palms in southern Nigeria. *J. W. Afr. Inst. Oil Palm Res.*, **3**, 16–51 [3.5.2.1]
- Tinker P.B. & Ziboh C.O. (1959b) Soil analysis and fertilizer response. *J. W. Afr. Inst. Oil Palm Res.*, **3**, 52–75 [11.5.1]
- Tinker P.B., Jones M. & Durrall D.M. (1992) A functional comparison of ecto- and endo-mycorrhizas. In: *Mycorrhizas in ecosystems* (Ed. by D.J. Read *et al.*), pp. 303–310, CAB International, Wallingford [11.2.2]
- Tinker P.B., Ingram J.S.I. & Struwe S. (1996) Effects of slash-and-burn agriculture and deforestation on climate change. *Agr. Ecosyst. Environ.*, **58**, 13–22 [1.4.3.8]
- Tiong R.H.C. (1979) Some predators and parasites of *Mahasena corbetti* (Tams) and *Thoesa asigna* (Moore) in Sarawak. *Planter, Kuala Lumpur*, **55**, 279–289 [12.2.5.1]
- Tiong R.H.C. (1982) Study of some aspects of biology and control of *Thoesa asigna* (Moore). In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 529–542, Incomp. Soc. Planters, Kuala Lumpur [12.2.5.1]
- Tiong R.H.C. & Munroe D.D. (1977) Microbial control of an outbreak of *Darna trima* (Moore) on oil palm (*Elaeis guineensis*, Jacq.) in Sarawak (Malaysian Borneo). In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 624–639, Incomp. Soc. Planters, Kuala Lumpur [12.2.5.1]
- Tirtoboma (1998) Culturability of oil palm microspore cells in relation to anther maturity. In: *Proc. BTIG Workshop 'Oil palm improvement through biotechnology'* (Ed. by J.S. Tahardi *et al.*), pp. 42–47, Biotechnol. Res. Unit for Estate Crops, Bogor, Indonesia [6.6.1.1]
- Toh P.Y., Baskett J.P.C. & Adham A. (1988) Reclamation of mangrove swamps for oil palm cultivation. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 419–428, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [3.4.3.4; 8.3.6]
- Toh P.Y. & Poon Y.C. (1982) Effect of water management on field performance of oil palm on acid sulphate soils in Peninsular Malaysia. In: *Proc. Symp. Acid sulphate soils*, Bangkok [8.2.3]
- Tohiruddin L., Prabowo N.E. & Foster H.L. (2002) *Cause and correction of white stripe in oil palm*. Paper presented at 2002 Int. Oil Palm Conf., Indonesian Oil Palm Res. Inst., Bali, 8–12 July. [12.1.5.3]
- Tombs M.P. & Stubbs J.M. (1982) The absence of endogenous lipase from oil palm mesocarp. *J. Sci. Food Agric.*, **33**, 892–897 [13.3.3]
- Tomlinson P.B. (1961) *Anatomy of the monocotyledons. II. Palmae*, Oxford University Press, Oxford [2.2.1.3; 2.2.1.5]
- Toovey F.W. & Purvis C. (1956) Segregation from the *dura* × *pisifera* cross. *J. W. Afr. Inst. Oil Palm Res.*, **1** (4), 106–109 [5.1.5]
- Toro M., Silio L., Rodriganez J., Rodriguez C. & Fernandez J. (1999) Optimal use of genetic markers in conservation programmes. *Genet. Select. Evol.*, **31**, 255–261 [5.1.7.5]
- Toruan-Mathius N., Haris N. & Ginting G. (1998) Use of bio-molecular techniques in studies of abnormalities in oil palm clones. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), pp. 308–314, Indonesian Oil Palm Res. Inst., Medan, Indonesia [6.3.3]
- Tregear J.W., Morcillo F., Richaud F., Berger A., Singh R., Cheah S. C., Hartmann C., Rival A. & Duval Y. (2002) Characterization of a defensin gene expressed in oil palm inflorescences: induction during tissue culture and possible association with epigenetic somaclonal variation events. *J. exp. Bot.*, **53**, 1387–1396 [6.3.3]
- Turner P.D. (1965a) The incidence of *Ganoderma* disease of oil palms in Malaya and its relation to previous crop. *Ann. appl. Biol.*, **55**, 417–423 [12.1.6.3]
- Turner P.D. (1965b) Oil palms and *Ganoderma* – is there a problem? *Planter, Kuala Lumpur*, **41**, 187–189 [12.1.6.3]
- Turner P.D. (1965c) Infection of oil palms by *Ganoderma*. *Phytopathology*, **55**, 937 [12.1.6.3]
- Turner P.D. (1965d) *Marasmius* infection of oil palms in Malaya – a review. *Planter, Kuala Lumpur*, **41**, 387–393 [12.1.8]
- Turner P.D. (1966a) Infection of oil palms by *Ganoderma* in Malaya. *Oléagineux*, **21**, 73–76 [12.1.6.3]
- Turner P.D. (1966b) Blast disease in oil palm nurseries. *Planter, Kuala Lumpur*, **42**, 102–108 [12.1.4]
- Turner P.D. (1968) The use of surgery as a method of treating basal stem rot in oil palms. *Planter, Kuala Lumpur*, **44**, 302–308 [12.1.6.3]
- Turner P.D. (1969) Observations on the incidence, effects and control of upper stem rot in oil palms. In: *Progress in oil palm* (Ed. by P.D. Turner), pp. 143–153, Incomp. Soc. Planters, Kuala Lumpur [12.1.6.5]
- Turner P.D. (1970) *Spear rot disease on plantacion 'La Arenosa'*. Report to the Compania Colombiana de Desarrollo S.A. [12.1.7.2]
- Turner P.D. (1971) *Microorganisms associated with oil palm* (*Elaeis guineensis*, Jacq.). Commonwealth Mycological Institute, Phytopathological Papers, No. 14 [12.1.5.6]
- Turner P.D. (1973) An effective trap for *Oryctes* beetle in oil palms. *Planter, Kuala Lumpur*, **49**, 488–490 [12.2.4.1]
- Turner P.D. (1977) The effects of drought on oil palm yields in South-east Asia and the south Pacific region. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 673–694, Incomp. Soc. Planters, Kuala Lumpur [4.4.1; 4.4.4; 4.4.5.2]
- Turner P.D. (1978) Some aspects of natural pollination in oil palm (*Elaeis guineensis*). *Planter, Kuala Lumpur*, **54**, 310–328 [4.4.7.1]

- Turner P.D. (1981) *Oil palm diseases and disorders*, Oxford University Press, Kuala Lumpur [2.3.3; 7.2.4; 11.4.1.3; 12.1]
- Turner P.D. & Bull R.A. (1967) *Diseases and disorders of the oil palm in Malaysia*, Incomp. Soc. Planters, Kuala Lumpur [4.4.6; 12.1.5.3; 12.1.8]
- Turner P.D. & Gillbanks R.A. (1974) *Oil palm cultivation and management*, Incomp. Soc. Planters, Kuala Lumpur [4; 7; 8; 9; 10; 13]
- Turrell J.A. (1985) Purity characteristics and guideline specifications. In: 'Palm kernel and coconut oils', *Symp. Proc. No. 32*, pp. 18–29, British Food Manufacturing Industries Assoc., Leatherhead [13.2.2]
- Umaña C.H. (1998a) Estado del cultivo de la palma de aceite en Costa Rica. *Palmas (Bogotá)*, **19** (Special no.), 90–92 [1.4.3.10]
- Umaña C.H. (1998b) Desarrollo del cultivo de la palma de aceite en Centroamérica. *Palmas (Bogotá)*, **19** (Special no.), 266–272 [1.4.3.10]
- Umaña C.H., Chinchilla C.M. & Richardson D.L. (1990) Material de desarrollo avanzado en viveros de palma aceitera (*Elaeis guineensis* Jacq.). 2. Condiciones del sustrato. *Turrialba*, **40**, 440–451 [7.2.3]
- Unilever (1961) *Annual review of research*, Unilever Plantations Group, London [8.3.4.3]
- Urueta E.J. (1975) Insectos asociados con el cultivo de palma africana en Uraba (Antioquia) y estudio de su relación con la pudrición de la flecha, pudrición del cogollo. *Rev. Colomb. Entomol.*, **1**, 15–31 [12.1.7.2]
- USDA (1996) *Keys to soil taxonomy*, 7, United States Dept Agric., Washington, DC [3.4.1.2]
- Vallade J. (1966) Aspect morphologique et cytologique de l'embryon quiescent d'*Elaeis guineensis* Jacq. *C. R. Acad. Sci. Paris, Ser. D*, **262**, 856–859 [2.2.1]
- Vallejo G. & Cassalet C. (1975) Perspectivas del cultivo de los híbridos interspecíficos de noli (*Elaeis oleifera* (H.B.K.) Cortes) × palma africana de aceite (*Elaeis guineensis* Jacq.) en Colombia. *Revista Inst. Colomb. Agropec.*, **10**, 19–35 [2.3.2; 2.4]
- van de Lande H.L. (1983) Vascular wilt disease of oil palm (*Elaeis guineensis* Jacq.) in Para, Brazil. *Oil Palm News*, **27**, 6–10 [12.1.6.2]
- van de Lande H.L. (1993a) Spatio-temporal analysis of spear rot and marchitez sorpresiva in African oil palm in Surinam. *Neth. J. Pl. Pathol.*, **99**, 129–138 [12.1.7.2]
- van de Lande H.L. (1993b) *Studies on the epidemiology of spear rot in oil palm (Elaeis guineensis Jacq.) in Suriname*. Thesis, Wageningen Univ., Wageningen [12.1.7.2]
- van de Lande H.L. & Zadoks J.C. (1999) Spatial patterns of spear rot in oil palm plantations in Surinam. *Plant Pathol.*, **48**, 189–201 [12.1.7.2]
- van den Hove J. (1971) Un type de pourriture des racines du palmier à huile. *Oléagineux*, **26**, 153–154 [12.1.6.4]
- van der Belt H. (1981) Socio-economic characteristics of 'out-growers' linked to industrial oil palm plantations: the case of Dobombari, Cameroun. In: *Essays in rural sociology*, pp. 1–23, Wageningen Agric. Univ., Wageningen [1.4.3.7]
- van der Vossen H.A.M. (1969a) Areas climatically suitable for optimal oil palm production in the forest zone of Ghana. *Ghana J. Agric. Sci.*, **2**, 113–118 [3.2.2.3]
- van der Vossen H.A.M. (1969b) Oil palm breeding and seed production in Ghana. *Ghana J. Agric. Sci.*, **2**, 81–90 [5.1.3.2]
- van der Vossen H.A.M. (1974) *Towards more efficient selection for oil yield in the oil palm (Elaeis guineensis Jacquin)*. Thesis, Wageningen Univ., Wageningen [5.1.6; 5.1.6.1; 5.2.6.3; 5.3.2; 5.3.3.1; 5.3.3.2; 5.4.1.1]
- Vanderwey R. (1952a) *Notions de culture de l'Elaeis au Congo Belge*. Direction de l'Agriculture, des Forêts, des Elevages et de la Colonisation, Brussels [9.3.3.1; 9.4.2]
- Vanderwey R. (1952b) La prospection des palmeraies congolaises et ses premiers résultats. *Bull. Inf. Inst. Nat. Etude Agron. Congo Belge*, **1**, 357–382 [5.1.7.1; 5.4.2.3]
- Vanderwey R. (1953) Le croisement 'dura × pisifera' et ses premiers résultats. *Bull. Inf. Inst. Nat. Etude Agron. Congo Belge*, **2**, 123–136 [5.1.5]
- Vanderwey R. & Roels O. (1949) Les variétés d'*Elaeis guineensis* Jacquin du type *albescens* et *Elaeis melanococca* Gaertner (em. Bailey). Note préliminaire. *Publ. Inst. Nat. Etude agron. Congo Belge, Ser. Sci.*, **42**, 1–24 [2.2.2.7; 5.3.7.4]
- Vanderwey R., Rossignol J. & Miclotte H. (1947) Considérations sur les teneurs en eau et en huile de la pulpe des fruits d'*Elaeis*. *C. R. de la Semaine Agricole de Yangambi, Comm.*, **54**, 730 [5.2.4.2]
- van Duijn G. (2000) Technical aspects of trans reduction in margarines. *Ol Corps Gras Lipides*, **7**, 95–98 [14.3.4]
- van Heel W.A., Breure C.J. & Menendez T. (1987) The early development of inflorescences and flowers of the oil palm (*Elaeis guineensis* Jacq.) seen through the scanning electron microscope. *Blumea*, **32**, 67–78 [2.2.2.1–3; 4.4.1]
- van Kraalingen D.W.G., Breure C.J. & Spitters C.J.T. (1989) Simulation of oil palm growth and yield. *Agric. Forest Meteorol.*, **46**, 227–244 [4.1.4.3; 4.2; 4.2.2.3; 4.3.1.2; 4.3.5.2; 4.5.5]
- Vanlauwe B., Nwoke O.C., Diels J., Sangina N., Carsky R.J., Deckers J. & Merckx R. (2000) Utilisation of rock phosphate on a representative toposequence on the Northern Guinea savannah zone of Nigeria: response by *Mucuna pruriens*, *Lablab purpureus* and maize. *Soil Biol. Biochem.*, **32**, 2063–2077 [11.9.2.3]
- Vanlauwe B., Diels J., Sangina N. & Merckx R. (2001) *Integrated plant nutrition management in sub-saharan Africa*. CABI Publishing, Wallingford [3.4.3.10]
- Van Noordwijk M. (2001) *Adopting a generic tree-soil-crop interaction model for evaluation of current and alternative oil palm production systems*. Paper presented at 2001 Int. Palm Oil Conf., Kuala Lumpur [8.1.3.7]
- van Slobbe W.G. (1983) Control of *Castnia daedalus*, a major pest of the oil palm in Surinam. *Trop. Agric., Trinidad*, **60**, 172–174 [12.2.8.2]
- van Slobbe W.G. (1986) Speerrot (Pudrición del cogollo) en Surinam y Brasil. In: *IV Mesa Redonda Latinoamericana sobre palma aceitera*, pp. 110–112, Federación Nacional de Cultivadores de Palma de Colombia, Valledupar, Colombia [12.1.7.2]
- van Slobbe W.G. (1988) *Amarelecimento fatal at the oil palm estate Denpasa, Brazil*. Paper presented at Int. Seminar 'Spear rot syndrome in oil palm', 8–12 Mar., Paramaribo [12.1.7.2]
- van Slobbe W.G., Parthasarathy M.V. & Heslen J.A.J. (1978) Hartrot or fatal wilt of palms. II. Oil palm (*Elaeis guineensis*) and other palms. *Principes*, **22**, 15–25 [12.1.6.4]
- Varghese G., Chew P.S. & Lim J.K. (1976) Biology and chemically assisted biological control of *Ganoderma*. In: *Proc. 1975 Int. Rubber Conf.*, pp. 278–292, Kuala Lumpur [12.1.6.3]

- Veerappan P., Bilal M., Nazeeb M. & Loong S.G. (2000) Early performance and potential of semi-clonal D × P progenies. In: *Proc. Int. Planters Conf. 'Plantation tree crops in the new millennium: the way ahead'* (Ed. by E. Pushparajah), pp. 117–130, Incorp. Soc. Planters, Kuala Lumpur [5.4.5.2]
- Velayuthan A. (1975) Palm oil process control. *Planter, Kuala Lumpur*, 51, 386–402 [13.4.5.2]
- Velayuthan A. (1985) Product recovery – Pamol Plantations Sdn Bhd. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 305–315, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.5.2]
- Velayuthan A. & Chan K.L. (1983) Efficiency of palm oil extraction and quality control. In: *Proc. Regional Workshop 'Palm oil mill technology and effluent treatment'*, pp. 92–111, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.3.6; 13.4.5.2]
- Velázquez-Cágal M., Pérez-Castañeda G. & Corona-Sáez T. (2001) Oil palm (*Elaeis guineensis* Jacq.) plantations diagnosis in the South of the Veracruz State, Mexico. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 578–586, Malaysian Palm Oil Board, Kuala Lumpur [1.4.3.12]
- Venugopal R. (1999) Policy issues relating to reverse investment in oil palm industry. In: *Proc. 1996 Seminar 'Sourcing of oil palm planting materials for local and overseas joint ventures'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 1–7, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.2]
- Vessey J.C. (1981) Lutte contre une maladie foliaire du palmier à huile au Honduras à l'aide d'insecticides. *Oléagineux*, 36, 229–232 [12.1.5.2]
- Vesterager J.H., Osterby S., Jensen E.S. & Schorring J.K. (1995) Symbiotic N₂ fixation by the cover crop *Pueraria phaseoloides* as influenced by litter mineralisation. *Pl. Soil*, 177, 1–10 [8.4.2]
- Villalobos E., Umaña C.H. & Chinchilla C.M. (1992) Estado de hidratación de la palma aceitera, en respuesta a la sequía en Costa Rica. *Oléagineux*, 47, 217–223 [3.3.3]
- Vine H. (1956) Studies of soil profiles at the WAIFOR main station and at some other sites of oil palm experiments. *J. W. Afr. Inst. Oil Palm Res.*, 1 (4), 8–59 [3.5.2.1]
- Vis J.K., Smith B.G. & Corley R.H.V. (2001) Sustainable agriculture – Unilever's view. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 233–243, Malaysian Palm Oil Board, Kuala Lumpur [1.4.2.4; 1.5.4; 8.2.1; 11.6.1; 15.3.4]
- Voituriez T. (1998) Long-run and short-run dynamics of palm oil market. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'*, (Ed. by A. Jatmika *et al.*), pp. 527–534, Indonesian Oil Palm Res. Inst., Medan, Indonesia [14.1.1]
- von Mohl H. (1849) The structure of the palm stem. In: *Reports and papers on botany*, pp. 3–94, The Ray Society, London [11.2.1.1]
- Vouyouklis G.V. (1981) Une méthode d'isolement de protoplastes du palmier à huile *Elaeis guineensis* Jacq. *Phyton*, 40, 169–178 [6.6.1.2]
- WAIFOR (1955) *Third Annual Report, 1954–55*, West African Inst. Oil Palm Res., Benin City [9.1.1]
- WAIFOR (1956) *Fourth Annual Report, 1955–56*, West African Inst. Oil Palm Res., Benin City. [2.2.1.4]
- Wainwright J. (1995) Use of phytometers for determining spatial variation in understory yields in oil palm agroforestry. In: *Ecophysiology of tropical intercropping* (Ed. by H. Sinoquet & P. Cruz) [8.4.3.2]
- Wakefield O.F. (1981) Factors affecting the viability of mechanising oil palm harvesting operations. In: *Proc. Workshop 'Farm mechanisation in the oil palm industry'*, pp. 52–75, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.4.7]
- Walworth J.L. & Sumner M.E. (1987) The diagnosis and recommendation integrated system (DRIS). *Adv. Soil Sci.*, 6, 149–188 [11.4.3]
- Walworth J.L. & Sumner M.E. (1988) Foliar diagnosis – a review. *Adv. Pl. Nutr.*, 3, 193–242 [11.4.3; 11.6.4.4]
- Wan C.K. (1987) Development of parthenocarpic fruits in oil palm (*Elaeis guineensis* Jacq.) due to application of herbicides. *Planter, Kuala Lumpur*, 63, 90–95 [2.2.2.7]
- Wan C.K. & Hor H.L. (1983) A study on the effect of certain growth substances on germination of oil palm (*Elaeis guineensis* Jacq.) seeds. *Pertanika J. trop. Agric. Sci.*, 6(2), 45–48 [7.1.1.3]
- Wan D. (1973) The use of buffaloes in oil palm fruit collection. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 432–437, Incorp. Soc. Planters, Kuala Lumpur [10.4.5]
- Wanasuria S. & Gales K. (1990) Copper deficiency of oil palm on mineral soils in Sumatra. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 431–439, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.4.1.3; 11.8.5]
- Wardlaw C.W. (1946a) *Fusarium oxysporum* on the oil palm. *Nature*, 158, 172 [12.1.5.5]
- Wardlaw C.W. (1946b) A wilt disease of the oil palm. *Nature*, 158, 56 [12.1.6.2]
- Wardlaw C.W. (1950a) *Armillaria* root and trunk rot of oil palms in the Belgian Congo. *Trop. Agric., Trinidad*, 27, 95–97 [12.1]
- Wardlaw C.W. (1950b) Vascular wilt disease of the oil palm caused by *Fusarium oxysporum* Schl. *Trop. Agric., Trinidad*, 27, 42–47 [12.1.6.2]
- Warriar S.M. & Piggott C.J. (1973) Rehabilitation of oil palms by corrective manuring based on leaf analysis. In: *Advances in oil palm cultivation*, (Ed. by R.L. Wastie & D.A. Earp), pp. 289–305, Incorp. Soc. Planters, Kuala Lumpur [11.1.3.2]
- Warwick D.R.N. & Bezerra A.P.T. (1992) Possible root transmission of the red-ring nematode (*Rhadinaphelenchus cocophilus*) to coconut palms. *Pl. Disease*, 76, 809–811 [12.1.6.6]
- Washburn R.A. (1973) The African oil palm in Costa Rica. *Oil Palm News*, 16, 1–2 [10.4.7]
- Waterston J.M. (1953) Observations on the influence of some ecological factors on the incidence of oil palm diseases in Nigeria. *J. W. Afr. Inst. Oil Palm Res.*, 1 (1), 24–59 [1.1.3]
- Wattanachant C., Dahlan I., Zulkifli A. & Rajion M.A. (1997) Sheep–oil palm integration: growth performance of Dorset × Nalin and Dorset × Siamese Long Tail sheep. *Pertanika J. trop. Agric. Sci.*, 20, 169–173 [8.4.3.4]
- Wattanachant C., Dahlan I., Alimon A.R. & Rajion M.A. (2001) Sheep–oil palm integration: grazing preference, nutritive value, dry matter intake and digestibility of herbage. *Asian Austr. J. Anim. Sci.*, 12, 209–214 [8.4.3.4]
- Webster C.C. (1983) Plantations and development: rubber and oil palms in South East Asia. *Trop. Agric. Assoc. Newslett.*, 3(1), 2 [1.5.2]
- Weir G.M. (1968) Leaf spot of the oil palm caused by *Cercospora elaeidis* Stey. Aspects of atmospheric humidity and temperature. *J. Nigerian Inst. Oil Palm Res.*, 5, 41–55 [12.1.2.1]
- Wessel M. (1992) Development of tree crop production systems in the lowlands of the humid tropics, and its relevance to agroforestry. *Trop. Crops Comm. (Neth.)*, 19, 1–17 [8.4.3.3]

- Wessels-Boer J.G. (1965) *The indigenous palms of Surinam*. Thesis, Univ. Leiden, Leiden [2.1; 2.3]
- West M.J., Ross J.M., Obasola C.O. & Mekko H.U. (1977) The inheritance of yield and of fruit and bunch composition characters in the oil palm – an analysis of the NIFOR main breeding programme. In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 95–105, Incomp. Soc. Planters, Kuala Lumpur [5.1.6.1; 5.3.2; 5.3.3.2; 5.4.2.1]
- White R.E. (1997) *Introduction to the principles and practices of oil science*, Blackwell Science, Oxford [3.4.1.1; 8.1.3.4; 8.1.3.6; 11.6.1.3]
- Widiastuti H., Darmono T.W. & Goenadi D.H. (1998) Response of oil palm seedlings to selected AM fungi inoculated at several doses of fertilisation. *Menara Perkebunan*, **66**, 36–46 [11.2.2]
- Wild A. (Ed.) (1988) *Russell's soil conditions and plant growth*, 11th edn, Longmans, Harlow and Wileys, New York [3.4.1.1]
- Wilkie A.S. & Foster H.L. (1990) Oil palm responses to fertilisers in Papua New Guinea. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 395–405, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.3.2.3; 11.4.5.1]
- Williams C.N. & Thomas R.L. (1970) Observations on sex differentiation in the oil palm, *Elaeis guineensis* L. *Ann. Bot.*, **34**, 957–963 [2.2.2.4; 4.4.4.3]
- Williams T.H. (1965) Diseases of the oil palm in Sabah. In: *Proc. Oil Palm Seminar*, pp. 56–63, Sabah Planters' Assoc. [12.1.5.6]
- Wilson R.F., Marquardt T.C., Novitzky W.P., Burton J.W., Wilcox J.R., Kinney A.J. & Dewey R.E. (2001) Metabolic mechanisms associated with alleles governing the 16:0 concentration of soybean oil. *J. Amer. Oil Chem. Soc.*, **78**, 335–340 [6.6.2.1]
- Wilson-Bibiano Y.V., Velázquez-Cágal M., Pérez-Mercado M., Corona-Sáez T. & Corona-Torres T. (2001) Edaphic and foliar nutritional state in palm oil (*Elaeis guineensis* Jacq.) plantations in the South of the Veracruz State, Mexico. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 557–561, Malaysian Palm Oil Board, Kuala Lumpur [3.5.3]
- Wong C.C. (1998) Soil compaction under cattle grazing in oil palm. *J. Trop. Agric. Food Sci.*, **26**, 203–210 [8.4.3.4]
- Wong C.Y. (1977) *Isolation of protoplasts from oil palm* (*Elaeis guineensis* Jacquin). Thesis, University of Malaya, Kuala Lumpur [6.6.1.2]
- Wong G., Tan C.C. & Soh A.C. (1997) Large scale propagation of oil palm clones – experiences to date. *Acta Hort.*, **447**, 649–658 [6.2.1.2]
- Wong G., Chong S.P., Tan C.C. & Soh A.C. (1999a) Liquid suspension culture – a potential technique for mass production of oil palm clones. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 3–11, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.3.1.1; 6.5.1.1; 6.5.2]
- Wong G., Tan C.C., Soh A.C. & Chong S.P. (1999b) Clonal propagation of oil palm through tissue culture. *Planter, Kuala Lumpur*, **75**, 221–230 [6.2.1]
- Wong S. (1993) Prospects for Malaysian speciality fats in the oils and fats trade. In: *Proc. 1991 Int. Palm Oil Conf. – Promotion and marketing* (Ed. by Y. Basiron *et al.*), pp. 82–88, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [14.3.4]
- Wong Y.K. & Hardon J.J. (1971) *A comparison of different methods of assisted pollination in the oil palm*, Chemara Res. Stn Comm. (Agron.) 9, Seremban, Malaysia [4.4.7.1; 4.4.7.3]
- Wonkyi-Appiah J.B. (1973) Germination of *pisifera* oil palm seeds under plantation conditions. *Ghana J. Agric. Sci.*, **6**, 223–226 [7.1.4.5]
- Wonkyi-Appiah J.B. (1982) Comparison of the results of meso-carp oil determination by the direct and indirect methods in the oil palm (*Elaeis guineensis* Jacq.). *Oléagineux*, **37**, 589–593 [5.2.4.2]
- Wonkyi-Appiah J.B. (1987) Genetic control of fertility in the oil palm (*Elaeis guineensis* Jacq.). *Euphytica*, **36**, 505–511 [5.3.3.1]
- Wonkyi-Appiah J.B. (1998) Oil and kernel content of OPRI materials. In: *Proc. 1996 Int. Conf. 'Oil and kernel production in oil palm – a global perspective'* (Ed. by N. Rajanaidu, I.E. Henson & B.S. Jalani), pp. 271–305, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.1]
- Wonkyi-Appiah J.B. (1999) Oil palm breeding in Ghana. In: *Proc. Seminar 'Science of oil palm breeding'* (Montpellier, 1992) (Ed. by N. Rajanaidu & B.S. Jalani), pp. 165–189, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.6.1]
- Wood B.J. (1966) Insect pests of oil palms in Malaya. *Planter, Kuala Lumpur*, **42**, 311–315 [12.2.5.1]
- Wood B.J. (1968a) *Pests of oil palms in Malaysia and their control*, Incomp. Soc. Planters, Kuala Lumpur [12.1.5.6; 12.2; 12.3]
- Wood B.J. (1968b) Studies on the effect of ground vegetation on infestation of *Oryctes rhinoceros* (L.) (Col., Dynastidae) in young oil palm replantings in Malaysia. *Bull. ent. Res.*, **59**, 85–96 [12.2.4.1]
- Wood B.J. (1970) Sources of reinfestation of oil palms by the wood rat (*Rattus tiomanicus*). In: *Crop protection in Malaysia* (Ed. by R.L. Wastie & B.J. Wood), pp. 146–164, Incomp. Soc. Planters, Kuala Lumpur [12.3.1]
- Wood B.J. (1971) Development of integrated control programs for pests of tropical perennial crops in Malaysia. In: *Biological control* (Ed. by C.B. Huffaker), pp. 422–457, Plenum Press, New York [12.2; 12.2.1; 12.2.1.1]
- Wood B.J. (1976a) Insect pests in South East Asia. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 347–367, Elsevier, Amsterdam [12.2.4.1; 12.5.2]
- Wood B.J. (1976b) Vertebrate pests. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 395–418, Elsevier, Amsterdam [9.1.4.3; 12.3.1]
- Wood B.J. (1976c) Pests – introduction and ecological considerations. In: *Oil palm research* (Ed. by R.H.V. Corley, J.J. Hardon & B.J. Wood), pp. 333–346, Elsevier, Amsterdam [12.2; 12.2.1; 12.2.1.1; 12.2.1.3]
- Wood B.J. (1977) The economics of crop protection in oil palms. *PANS*, **23**, 253–267 [12.2.5; 12.3.1; 12.3.2]
- Wood B.J. (1979) Progress in the development of integrated pest control programmes in Malaysian agriculture. In: *Strategies in plant protection* (Ed. by Lim T.K. *et al.*), pp. 176–216, Malaysian Plant Protection Soc., Kuala Lumpur [12.2; 12.2.1; 12.2.1.1; 12.2.1.2]
- Wood B.J. (1983a) Oil palm pests. In: *Exotic plant quarantine pests and procedures for introduction of plant materials* (Ed. by K.G. Singh), pp. 53–66, Asean Plant Quarantine Centre, Serdang, Malaysia [12.2]
- Wood B.J. (1983b) Note on insect pollination of oil palm in South and Central America. *Planter, Kuala Lumpur*, **59**, 167–170 [2.2.2.5]
- Wood B.J. (1984) A long-term study of *Rattus tiomanicus* populations in an oil palm plantation in Johore, Malaysia I. Study

- methods and population size without control. *J. appl. Ecol.*, **21**, 445–464 [12.3.1]
- Wood B.J. (1985) Biological control of vertebrates – a review and an assessment of prospects for Malaysia. *J. Pl. Protection Trop.*, **2**, 67–79 [12.3.1]
- Wood B.J. (1987) Economic aspects and chemical control. In: *Slug and nettle caterpillars* (Ed. by M.J.W. Cock, H.C.J. Godfray & J.D. Holloway), pp. 223–256, CAB International, Wallingford [12.2; 12.2.1; 12.2.1.1; 12.2.5.1]
- Wood B.J. (1999) *Cases illustrating the need for continuing R&D in IPM in oil palm*. Paper presented at 1999 Crop Protection Conf., Kuala Lumpur [12.1.6.3; 12.2.4.1]
- Wood B.J. & Beattie T.E. (1981) Processing and marketing of palm oil. *Planter, Kuala Lumpur*, **57**, 379–400 [1.4.3.2; 1.6.2]
- Wood B.J. & Chung G.F. (1990) Warfarin resistance of *Rattus tiomanicus* in oil palms in Malaysia and the associated increase of *Rattus diardii*. In: *Proc. 14th Vertebrate Pest Conf.* (Ed. by L.R. Davis, R.E. Marsh & D.E. Beadle), pp. 129–134, University of California, Davis, CA [12.3.1]
- Wood B.J. & Corley R.H.V. (1993) The energy balance of oil palm cultivation. In: *Proc. 1991 PORIM Int. Palm Oil Conf. – Agriculture*, (Ed. by Y. Basiron & B.S. Jalani), pp. 130–143, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.1; 14.3.6.1]
- Wood B.J. & Liao S.S. (1984a) A long-term study of *Rattus tiomanicus* populations in an oil palm plantation in Johore, Malaysia II. Recovery from control and economic aspects. *J. appl. Ecol.*, **21**, 465–472 [12.3.1]
- Wood B.J. & Liao S.S. (1984b) A long-term study of *Rattus tiomanicus* populations in an oil palm plantation in Johore, Malaysia. III. Bionomics and natural regulation. *J. appl. Ecol.*, **21**, 473–495 [12.3.1]
- Wood B.J. & Nesbit D.P. (1969) Caterpillar outbreaks on oil palms in eastern Sabah. *Planter, Kuala Lumpur*, **45**, 285–299 [12.2.5.1]
- Wood B.J. & Ng K.Y. (1969) The cockchafer, *Psilopholis vestita*, a new pest of oil palms in West Malaysia. *Planter, Kuala Lumpur*, **45**, 577–586 [12.2]
- Wood B.J. & Ng K.Y. (1974) Studies on the biology and control of the oil palm bunch moth, *Tirathaba mundella* (Walker) (Lepidoptera: Pyralidae). *Malay. agric. J.*, **49**, 310–331 [12.2.8.1]
- Wood B.J. & Nicol I. (1972) Rat control on oil palm estates. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 380–395, Incomp. Soc. Planters, Kuala Lumpur [12.3.1]
- Wood B.J., Corley R.H.V. & Goh K.H. (1973) Studies on the effect of pest damage on oil palm yield. In: *Advances in oil palm cultivation* (Ed. by R.L. Wastie & D.A. Earp), pp. 360–377, Incomp. Soc. Planters, Kuala Lumpur [4.2.2.1; 4.3.6.3; 12.2; 12.2.1.2; 12.2.4.1; 12.2.5]
- Wood B.J., Liao S.S. & Knecht J.C.X. (1974) Trunk injection of systemic insecticides against the bagworm, *Metisa plana* (Lepidoptera: Psychidae) on oil palm. *Oléagineux*, **29**, 499–505 [12.2.1.4; 12.2.5.2]
- Wood B.J., Hutauruk C. & Liao S.S. (1977) Studies on the chemical and integrated control of the nettle caterpillars (Lepidoptera: Limacodidae). In: *International developments in oil palm* (Ed. by D.A. Earp & W. Newall), pp. 591–616, Incomp. Soc. Planters, Kuala Lumpur [12.2.5.1]
- Wood B.J., Ismail S., Loong S.G. & Chew S.C. (1985a) A preliminary report on a long-term study of the effect of oil palm harvesting strategy on product recovery, including a comparison before and after weevil pollination. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 187–219, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [10.5.2]
- Wood B.J., Loong S.G., Ismail S., Lee M.H. & Quah S.K. (1985b) Mill recovery of palm oil from FFB harvested to various 'ripeness' standards. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 255–266, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [13.4.5.2]
- Wood B.J., Ismail S., Hon D., Gan L.T. & Ng S.K. (1987) A measurement of achieved palm oil extraction ratios against the potential. *Planter, Kuala Lumpur*, **63**, 337–357 [10.5.2; 13.4.5.2]
- Wood B.J., Chung G.F. & Sim S.C. (1988) The rise of *Rattus rattus diardii* as an oil palm pest. In: *Proc. 1987 Int. Oil Palm Conf. 'Progress and prospects'* (Ed. by A. Halim Hassan *et al.*), pp. 493–505, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.3.1]
- Wood B.J., Chung G.F. & Sim S.C. (1990) The occurrence and control of warfarin resistant rats in oil palms. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 317–341, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [12.3.1]
- Wooi K.C. (1990) Oil palm (*Elaeis guineensis* Jacq.): tissue culture and micropropagation. In: *Biotechnology in agriculture and forestry 10: Legumes and oilseed crops I* (Ed. by Y.P.S. Bajaj), pp. 569–592, Springer, Berlin [6.1; 6.2.1.2; 6.2.1.3]
- Wooi K.C. (1995) Oil palm tissue culture – current practice and constraints. In: *Recent developments in oil palm tissue culture and biotechnology* (Ed. by V. Rao, I.E. Henson & N. Rajanaidu), pp. 21–32, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.2.1; 6.2.1.1]
- Wooi K.C., Wong C.Y. & Corley R.H.V. (1981) Tissue culture of palms – a review. In: *Proc. COSTED Symp. 'Tissue culture of economically important plants'* (Ed. by A.N. Rao), pp. 138–144, Singapore [6.2.1.1; 6.2.1.4]
- Wooi K.C., Wong C.Y. & Corley R.H.V. (1982) Genetic stability of oil palm callus cultures. In: *Proc. 5th Int. Congr. 'Plant tissue and cell culture'* (Ed. by A. Fujiwara), pp. 749–750, Jpn. Soc. Plant Tissue Culture, Tokyo [6.3]
- World Bank. (1995) *World Bank Atlas*. World Bank, Washington, DC [8.2.1]
- Wormer T.M. & Ochs R. (1959) Humidité du sol, ouverture des stomates et transpiration du palmier à huile et de l'arachide. *Oléagineux*, **14**, 571–580 [10.3.1.2]
- Wuidart W. & Konan K. (1989) Weaning oil palm ramets. *Oléagineux*, **44**, 573–582 [6.2.1.4]
- Xavier A. (2000) Fertiliser requirement of oil palms for high yields: some thoughts. In: *Managing oil palm for high yields: agronomic principles*, (Ed. by Goh K.J.), pp. 74–97, Malaysian Society of Soil Science and Param Agricultural Surveys, Kuala Lumpur [11.1.4; 11.7.1]
- Xu X.B. (2000) Production of specific-structured triacylglycerols by lipase-catalyzed reactions: a review. *Eur. J. Lipid Sci. Technol.*, **102**, 287–303 [14.3.1; 14.3.3.3]
- Yampolsky C. (1922) A contribution to the study of the oil palm (*Elaeis guineensis*, Jacq.). *Bull. Jard. Bot., Buitenzorg*, **3**, 107–174 [2.2.1.5]
- Yampolsky C. (1924) The pneumathodes on the roots of the oil palm (*Elaeis guineensis*, Jacq.). *Amer. J. Bot.*, **11**, 502–512 [2.2.1.5]
- Yáñez E.E., Asis I. & García J.A. (2000) *Metología alterna de muestro y análisis fisicoquímico de racimos de palma de aceite*. Paper

- presented at Conf. 'Competitividad y prospectiva de la palma de aceite', 6–8 Sept., Cartagena, Colombia [5.2.4.2]
- Yao N.R., Orsot-Dessi D.D.S., Ballo K. & Fondio L. (1995) Decrease in rainfall in the Ivory Coast – future impact on the production of palm oil. *Secheresse*, **6**, 265–271 [3.3.1]
- Yeboua K. & Ballo K. (2000) Soil chemistry characteristics in an oil palm plantation. *Cahiers Agric.*, **9**, 73–76 [11.7.5]
- Yee C.B., Lim K.C., Ong E.C. & Chan K.W. (1985) The effects of *E. kamerunicus* on bunch components of *E. guineensis*. In: *Proc. Symp. 'Impact of the pollinating weevil on the Malaysian oil palm industry'*, pp. 129–139, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [4.4.7.1]
- Yeow K.H., Tam T.K., Poon Y.C. & Toh P.Y. (1982) Recent innovation in agronomic practice: palm replacement during immaturity. In: *The oil palm in agriculture in the eighties*, Vol. 2 (Ed. by E. Pushparajah & Chew P.S.), pp. 357–366, Incomp. Soc. Planters, Kuala Lumpur [9.1.5]
- Yong Y.Y. & Chan K.W. (1990) Evaluation of some Dumpy Avros D × P progenies at two locations for genotype × environment interaction. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 49–53, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.7]
- Yong Y.Y., Lee C.H., Tan S.T., Chiu S.B., Donough C.R., Ahmad Alwi & Chan K.W. (1993) Evaluation of *Elaeis oleifera* × *E. guineensis* interspecific hybrids at five locations for genotype × environment interaction. In: *Proc. 1991 Int. Soc. Oil Palm Breeders Workshop 'Genotype – environment interaction studies in perennial tree crops'*, pp. 55–62, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.5.1.7]
- Yong Y.Y., Chin P.P. & Chan K.W. (1999) Guthrie Chemara planting materials. In: *Proc. 1996 Seminar 'Sourcing of oil palm planting materials for local and overseas joint ventures'* (Ed. by N. Rajanaidu & B.S. Jalani), pp. 91–105, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [5.1.1.4; 5.1.6.2]
- Young E.C. (1986) The rhinoceros beetle project: history and review of the research programs. *Agric. Ecosyst. Environ.*, **15**, 149–166 [12.2.4.1]
- Yow S.T.K. & Jamaluddin Nasir (2001) Replanting policies and strategies in Golden Hope. In: *Proc. 2001 Int. Palm Oil Congr. – Agriculture*, pp. 289–294, Malaysian Palm Oil Board, Kuala Lumpur [8.3.4.2; 12.1.6.3]
- Yusoff M.S.A. (2000) Refining and modification of palm and palm kernel oil. In: *Advances in oil palm research*, Vol. 2 (Ed. by Y. Basiron, B.S. Jalani & Chan K.W.), pp. 783–805, Malaysian Palm Oil Board, Kuala Lumpur [13.2.2; 13.5.1]
- Zaharah A.R., Sharifuddin H.A.H., Ahmad Sahali M. & Hussein M.S. (1989) Fertilizer placement studies in mature oil palm using isotope technique. *Planter, Kuala Lumpur*, **65**, 384–388 [2.2.1.5; 11.2.1.3]
- Zainal Abidin (1998) Indonesian Government policy on the investment. In: *Proc. 1998 Int. Oil Palm Conf. 'Commodity of the past, today and the future'* (Ed. by A. Jatmika *et al.*), p. 27, Indonesian Oil Palm Res. Inst., Medan, Indonesia [1.4.3.1]
- Zainal Z. & Yusoff M.S.A. (1999) Enzymatic interesterification of palm stearin and palm kernel olein. *J. Amer. Oil Chem. Soc.*, **76**, 1003–1008 [14.3.4]
- Zainudin M.N., Ponjian K. & Yassin A.K.M. (2000) Implications of cattle integration on weeding in mature oil palm – YPJOPE's experience. *Planter, Kuala Lumpur*, **76**, 279–286 [8.4.3.4]
- Zambri M.P. & Zin Z.Z. (1995) Large planting hole technique – rationale for increased growth and high FFB yield. In: *Proc. 1995 Natm. Oil Palm Conf.*, pp. 1–13, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [9.1.1]
- Zamzuri I. (1999) Using double-layer technique in rooting of oil palm *in vitro* plantlets. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 223–229, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [6.5.1.1]
- Zamzuri I., Mohd Arif S., Rajanaidu N. & Rohani O. (1998) Clonal oil palm planting material production: an economic analysis. *Planter, Kuala Lumpur*, **74**, 597–619 [6.5.3]
- Zeddam J.L., Cruzado J.A., Rodriguez J.L., Ravallec M. & Subilete E.C. (2003) A cypovirus from the South American oil-palm pest *Norape argyrrhorea* and its potential as a microbial control agent. *Biocontrol*, **48**, 101–112 [12.2]
- Zelazny B. (1977) *Oryctes rhinoceros* populations influenced by a baculovirus. *J. Invertebrate Pathol.*, **29**, 210–215 [12.2.4.1]
- Zeven A.C. (1964) On the origin of the oil palm. *Grana palynol.*, **5**, 121–123 [1.1.1]
- Zeven A.C. (1965) Oil palm groves in southern Nigeria. Part I. Types of groves in existence. *J. Nigerian Inst. Oil Palm Res.*, **4**, 226–249 [1.1.2; 1.2.4]
- Zeven A.C. (1967) *The semi-wild oil palm and its industry in Africa*. Agric. Res. Rep. 689, Wageningen Univ., Wageningen [1.2.1; 1.2.4; 2.2.1.4; 4.4.5]
- Zeven A.C. (1968) Oil palm groves in southern Nigeria. Part II. Development, deterioration and rehabilitation of groves. *J. Nigerian Inst. Oil Palm Res.*, **5**, 21–39 [1.2.4]
- Zeven A.C. (1972) The partial and complete domestication of the oil palm (*Elaeis guineensis*). *Econ. Bot.*, **26**, 274–279 [1.2.4]
- Zeven A.C. (1973) The 'mantled' oil palm (*Elaeis guineensis* Jacq.). *J. W. Afr. Inst. Oil Palm Res.*, **5**(18), 31–33 [2.2.2.6; 5.3.3.3]
- Zimmermann M.H. & Tomlinson P.B. (1965) Anatomy of the palm *Rhapis excelsa* L. Mature vegetative axis. *J. Arnold Arboretum*, **46**, 160–178 [2.2.1.3]
- Zin Z.Z., Tarmizi Mohamad A., Foster H.L., Tayeb Dolmat M., Khalid H. & Hamdan A.B. (1990) Evaluation of urea as a nitrogen fertiliser for the oil palm industry in Malaysia. In: *Proc. 1989 Int. Palm Oil Dev. Conf. – Agriculture* (Ed. by B.S. Jalani *et al.*), pp. 440–446, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [11.9.2.2]
- Zin Z.Z., Ariffin D., Tarmizi Mohamad A., Azizah Hashim & Zambri M.P. (1996) *Effect of VAM inoculation on growth and yield of oil palm in peat soil*. Paper presented at Seminar 'Prospect of oil palm planting on peat in Sarawak – the golden opportunity' [2.2.1.5]
- Zulnerlin & Fatah Ibrahim A. (1999) Experience in zero burning in plantations of PTTP London Sumatra Indonesia Tbk. In: *Preprints, 1999 PORIM Int. Palm Oil Conf.*, pp. 55–63, Palm Oil Res. Inst. Malaysia, Kuala Lumpur [8.1.4; 8.3.2; 8.3.3.2; 8.3.3.3; 12.2.4.1; 12.2.6.1]

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Plate I (A) Palm with ripe orange bunches, unripe black bunches, and detached ripe fruit on the ground (Section 10.4.4). (B) Male inflorescence (Section 2.2.2.3). (C) Female inflorescence – note cream-coloured, tri-lobed stigmas (Section 2.2.2.2). (D) Ripe bunch, with detached fruit lodged against frond petiole (Sections 2.2.2.7, 10.4.4.2).

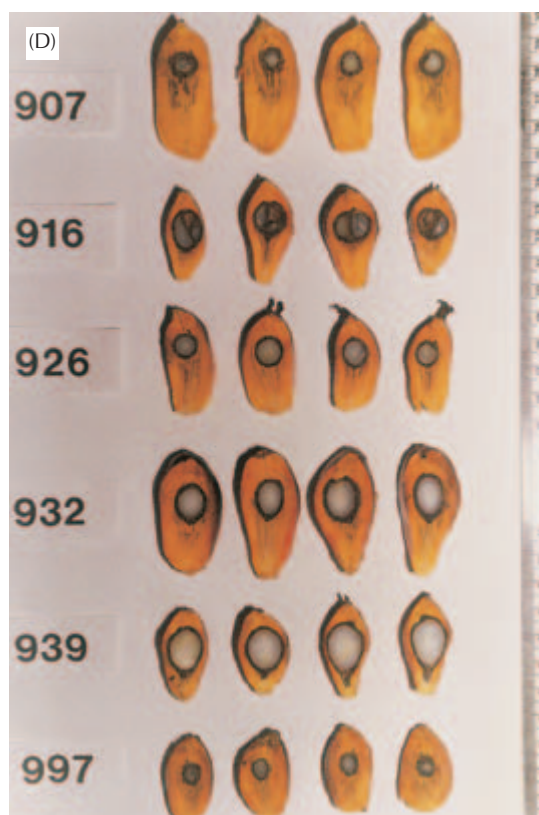
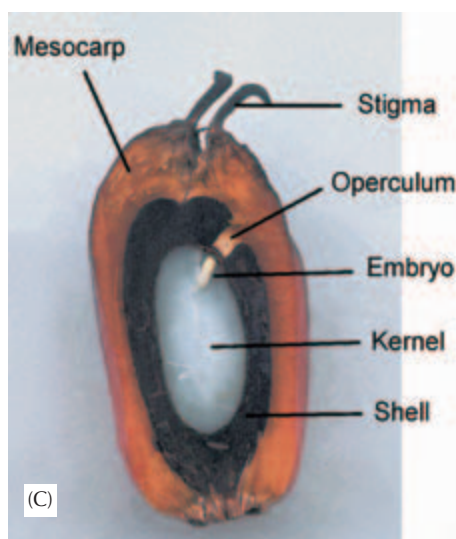


Plate II (A) Longitudinal and transverse sections of fruits of the three shell-thickness forms (Sections 2.2.2.6, 5.3.3.1). (B) Nearly ripe bunch (length about 40 cm; unpigmented fruits develop where the bunch is pressed tightly to the adjacent leaf base, so receives no light) (Sections 2.2.2.7, 10.5.3). (C) Cross-section of individual fruit (*dura* fruit form; length about 4 cm) (Section 2.2.2.6). (D) Cross-sections of fruit from 6 different *tenera* clones, showing a range of fruit and kernel sizes and shapes (Section 5.3.3.1).



(A)



(B)

Plate III (A) Fifteen-year-old palms in Malaysia, with dense ground cover of ferns and grasses, and epiphytic ferns on palm trunks (Section 10.1.2.2). (B) Two-year-old palms with legume cover crop (Section 10.1.2.3). (Pamol Plantations Sdn Bhd.) (C) NIFOR mini-mill. Right: steriliser; centre: digester-screw press; left, continuous clarifier (Section 13.4.4) (photo: U. Omoti). (D) NIFOR digester-screw press in operation; fruits are fed in at top right, palm oil collected at bottom left, and fibre and nuts at bottom centre (photo: U. Omoti).



(C)



(D)



Plate IV (A) Underplanting in Thailand – note alternate double rows of old stand remaining, and legume cover well established in cleared avenues (Section 8.3.4.3). (Photo: Univanich Palm Oil Public Co. Ltd.) (B) Liquid from anaerobic effluent ponds discharging into flat beds in the field, for recycling of nutrients (Section 11.7.2.2). (Pamol Plantations Sdn Bhd.) (C) Young palms planted on terraces that run along the contour (Section 8.3.5). (Pamol Plantations Sdn Bhd.) (D) Empty fruit bunches spread between palms as a mulch and for recycling of nutrients (Section 11.7.2.1). (Pamol Plantations Sdn Bhd.) (E) Tide gate for water management in low-lying plantation (Section 8.2.3). (Pamol Plantations Sdn Bhd.)



(A)

Plate V (A) Buffalo cart for in-field fruit transport in Malaysia (Section 10.4.5). (Pamol Plantations Sdn Bhd.) (B) Mini-tractor with hydraulic high-lift trailer, tipping fruit bunches into a container for transport to the mill (Section 10.4.6). (Pamol Plantations Sdn Bhd.) (C) Hydraulic 'grabber' attached to mini-tractor, for lifting bunches into trailer (Section 10.4.6). (Pamol Plantations Sdn Bhd.) (D, E) Loading and spreading empty fruit bunches from simple tipping buffalo cart (Section 11.7.2.1). (Pamol Plantations Sdn Bhd.)



(B)



(C)



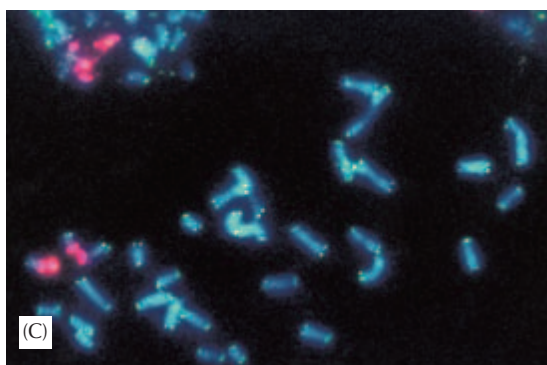
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(E)



Plate VI (A) *Elaeis oleifera*: palm with many ripe and unripe bunches in the Sinú valley, Colombia (Section 2.3). (B) Close-up of *virescens* palm – developing bunches are green, ripe bunch is orange (Sections 2.2.2.6, 5.3.3.3). (C) Metaphase chromosomes of oil palm ($2n = 32$) (From Castilho *et al.*, 2000). The chromosomes have been stained blue, after *in situ* hybridisation with probes for the 'telomeric sequence' (found at the end of the chromosome, and here fluorescing green at the tips of all 16 chromosome pairs), and an '18S-25S rDNA' probe (red, located on one chromosome pair) (Sections 2.2.1.6, 5.2.8.1). (D) Aerial view of breeding trial in Congo, showing differences in susceptibility to *Fusarium* wilt. Plots of susceptible palms are yellowish or already dead. Tolerant palms remain dark green and healthy (Sections 5.3.5, 12.1.6.2).



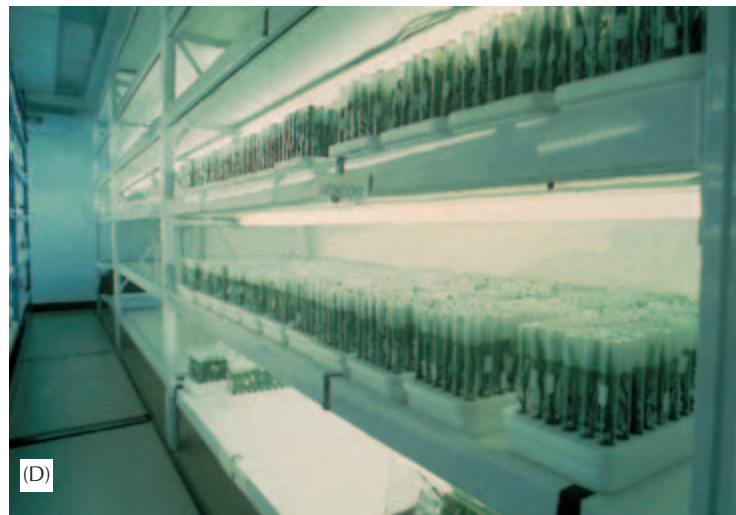
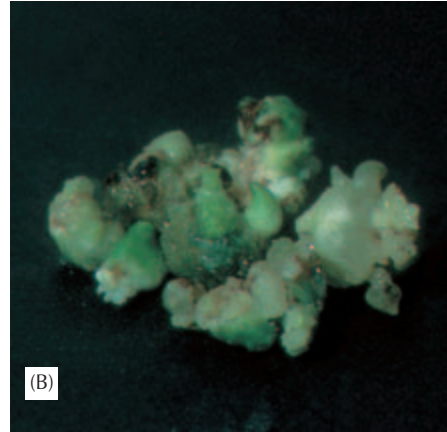
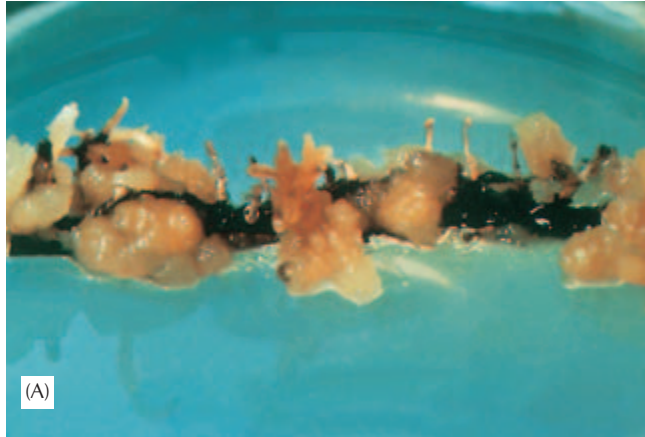


Plate VII Propagation of the oil palm by tissue culture (Section 6.2). (A) Primary callus developed on root explant. (B) Cluster of embryoids. (C) Embryoids with shoot. (D) Culture room with plants ready for despatch. (E) Young clonal plants in pre-nursery.



Plate VIII (A) Crown sampling for tissue culture in progress – all but youngest leaves from centre of crown have already been removed (Section 6.2.1.1). (B) The first three clonal oil palms, planted in Malaysia in 1977 (photographed in 2000). (Pamol Plantations Sdn Bhd.) (C) Mantled fruits, with fleshy outgrowths from rudimentary stamen primordia. (D) Cross-sections of mantled fruits (Sections 2.2.2.6, 5.3.3.3, 6.3.1). (E) Clonal plant showing ‘truncated leaf syndrome’ (Section 6.3.2). (F) Clonal plant with terminal inflorescence (Section 6.3.2).



Plate IX (A) Seedling showing acute N-deficiency symptoms on water-logged soil in Brazil (Section 11.4.1.3). (B) Magnesium deficiency symptoms in nursery (Section 11.4.1.3) (photo: J.M.A. Sly). (C) Magnesium deficiency in young palms in Colombia (Section 11.4.1.3). (D) Orange frond of the adult palm, Sierra Leone (Section 11.4.1.3).



Plate X (A–C) Various symptoms that have been attributed to potassium deficiency (Section 11.4.1.2). (A) Confluent orange spotting (photo: J.M.A. Sly). (B) Mid-crown yellowing; also some Mbwasi symptom (photo: J.M.A. Sly). (C) Mid-crown yellowing (photo: J.M.A. Sly). (D) The ‘peat yellows’ condition in palms growing on peat in Malaysia (Section 11.4.1.3).



Plate XI (A) Advanced stage of blast disease (Section 12.1.4) (photo: J.M.A. Sly). (B) Patch yellows (Section 12.1.5.5) (photo: J.M.A. Sly). (C) Leaf infected with *Pesalatiopsis* sp. in Colombia (Section 12.1.5.2). (D) Heavy losses to sudden wither (marchitez sorpresiva) in Colombia (Section 12.1.6.4).

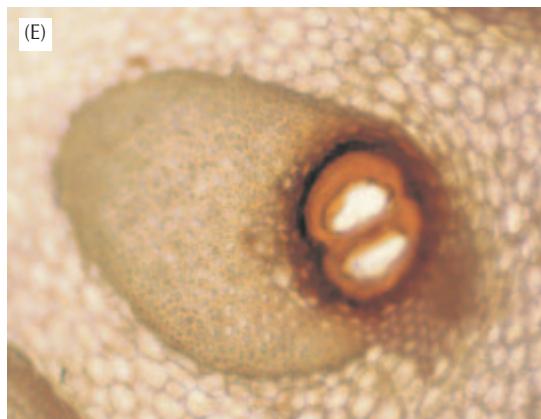


Plate XII *Fusarium* wilt (Section 12.1.6.2). (A) Symptoms of *Fusarium* wilt in young field palm; note that young fronds are shorter than desiccated older fronds. (B) Symptoms of wilt in mature field palm; note collapse of desiccated fronds, which break at some distance along the petiole and hang around the trunk. (C) Insertion of increment borer (auger) into oil palm trunk to test for infection by *Fusarium oxysporum* f.sp. *elaeidis* (photo: J. Flood). (D) Comparison of increment borer cores from infected (below) and uninfected (above) palms (photo: R. Mepsted). (E) Microscopic view of brown staining of xylem vessels in a core from an infected palm (photo: R. Mepsted).



Plate XIII *Fusarium* wilt (Section 12.1.6.2). (A) Nursery wilt test, showing two resistant (far left, near right) and two susceptible (near left, far right) families (Section 5.3.5). (B) Transverse section through oil palm root showing *Fusarium* hyphae in xylem vessels (photo: R. Mepsted). (C) Transverse section through oil palm root showing 'tyloses' occluding a large xylem vessel (photo: R. Mepsted). (D) Longitudinal section through uninfected nursery seedling (photo: J. Flood). (E) Longitudinal section through infected seedling, showing black staining of vascular elements characteristic of this disease.

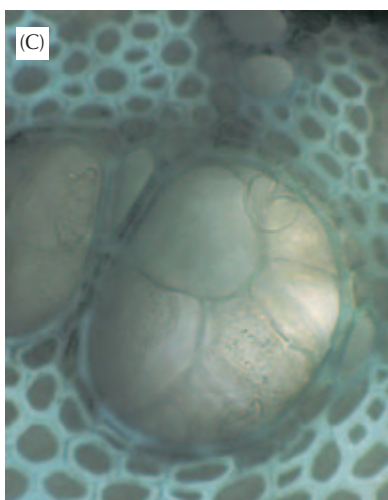
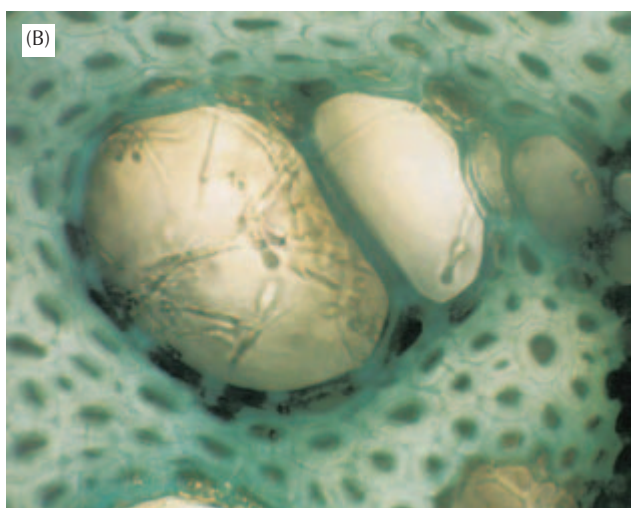




Plate XIV *Ganoderma* basal stem rot (Section 12.1.6.3). (A) Sporophores of *Ganoderma* on oil palm trunk (photo: R. Miller). (B) Fallen palm, showing base of trunk entirely rotted (photo: J. Flood). (C) Symptoms of *Ganoderma* infection in adult palm: multiple unopened spears, yellowing and wilting of older fronds (photo: J. Flood). (D) Base of trunk of mature palm, mounded with soil (covered with cut fronds to reduce drying) as a method of reducing losses from *Ganoderma* (photo: J. Flood).



Plate XV (A) Young palm affected by crown disease in Colombia (Section 12.1.5.1). (B) Upper stem rot, caused by *Ganoderma* – trunk has snapped, and crown fallen (Section 12.1.6.5) (photo: J. Flood). (C) Symptoms of ‘chronic’ form of fatal yellowing in Brazil – palm continues to produce small new leaves (Section 12.1.7.2). (D) Early symptoms of fatal yellowing in Colombia (Pacific coast) – youngest leaves yellowed and falling (Section 12.1.7.2).



Plate XVI (A) Defoliation caused by nettle caterpillar *Setora nitens* in Sumatra (Section 12.2.5.1) (photo: B.J. Wood). (B) *Setora nitens* caterpillar (length c. 4 cm) (Section 12.2.5.1) (photo: B.J. Wood). (C) Larva of leaf miner *Coelaenomenodera lameensis* (length c. 5 mm), with necrotic leaf tissue of old gallery (Section 12.2.5.5) (photo: B.J. Wood). (D) *Setora nitens* caterpillar parasitised by *Spinaria spinator* (photo: B.J. Wood). (E) Bagworm *Mahasena corbetti* (length c. 3.5 cm) (Section 12.2.5.2).

